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LONGITUDINAL SEPARATION ANALYSIS OF THE CENTRAL EAST PACIFIC TR--ETC(U)
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LONGITUDINAL SEPARATION ANALYSIS OF THE CENTRAL EAST PACIFIC TRACK SYSTEM

Wayne E. Smoot

JUNE 1977

FINAL REPORT

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16. Abstract

This report represents an evaluation of aircraft mach number spacing and inertial navigation systems (INS) as regards their impact on longitudinal separation and collision risk in the Central East Pacific (CEP). A nomograph was produced for predicting maximum expected changes in longitudinal separation of aircraft flying with mach number spacing on long-distance transoceanic flights. Results indicate that a statistically significant difference in maintaining longitudinal separation exists between those aircraft employing mach number spacing techniques and those not using the techniques, and likewise between aircraft with more sophisticated air data systems than those without. Collision risk from loss of longitudinal separation was found to be at an acceptable level, both in the old and current CEP systems.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF TABLES

LIST OF TABLES (CONT'D)

INTRODUCTION

PURPOSE.

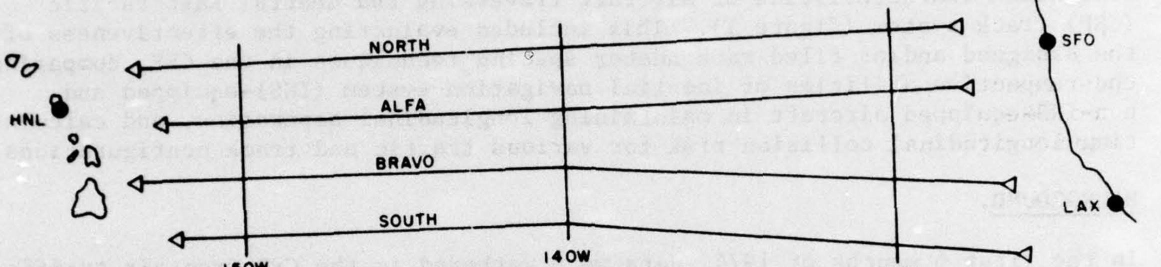
The purpose of this study conducted at the National Aviation Facilities Experimental Center (NAFEC) was to analyze the longitudinal (i.e., along-track) separation characteristics of aircraft traversing the Central East Pacific (CEP) track system (figure 1). This included evaluating the effectiveness of the assigned and/or filed mach number spacing techniques in the CEP, comparing the respective abilities of inertial navigation system (INS)-equipped and non-INS-equipped aircraft in maintaining longitudinal separation, and calculating longitudinal collision risk for various traffic and track configurations.

BACKGROUND.

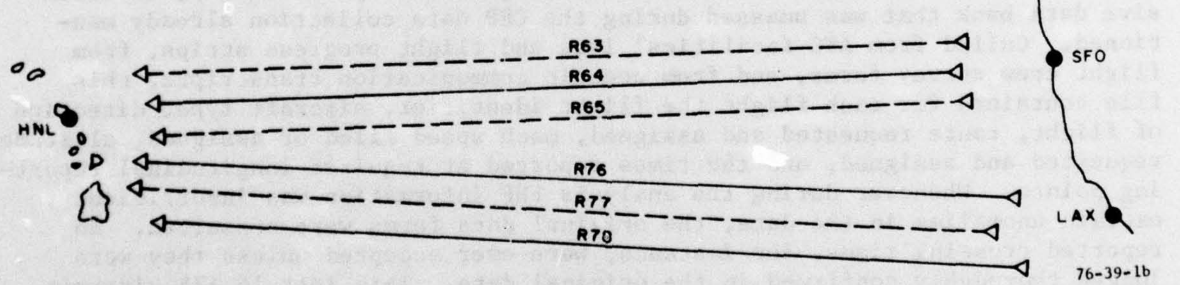
In the first 6 months of 1974, data were gathered in the CEP from air traffic control (ATC) and user sources in order to monitor and describe flights across the system. An ever-increasing commercial and military demand for optimum routes and altitudes had led the United States to undertake an evaluation of composite separation as a means of increasing system capacity, and these data, collected between December 15, 1973, and June 30, 1974, served extensively in that evaluation (reference 1).

In accordance with agreements made at the Asia/Pacific Regional Air Navigation (Asia/PAC/RAN) conference in Honolulu in September 1973, a further analysis of the CEP data was completed in the spring of 1976 by the Analysis Branch of NAFEC. The data utilized resided in the Flight History File (FHF), an extensive data bank that was amassed during the CEP data collection already mentioned. Culled from ATC facilities' logs and flight progress strips, from flight crew survey forms, and from oceanic communication transcripts, this file contained for each flight the flight identifier, aircraft type, direction of flight, route requested and assigned, mach speed filed or assigned, altitude requested and assigned, and the times reported at required longitudinal reporting points. Whenever during the analysis FHF information was insufficient to explain anomalies in the data, the original data forms were consulted. No reported crossing times, for instance, were ever accepted unless they were judged thoroughly confirmed in the original data. This left 16,478 aircraft of the original 18,164 available for analysis.

The following report presents the results of an analysis of the longitudinal separation characteristics of aircraft flying the CEP system. It should prove of interest and assistance to ATC operations personnel and to systems users in assessing route parameters and in proposing modifications to the CEP track structure.



A. FORMER CEP TRACK SYSTEM



B. COMPOSITE CEP TRACK SYSTEM (IMPLEMENTED MAY 20, 1976, FOR OPERATIONAL TRIAL)

FIGURE 1. CENTRAL EAST PACIFIC TRACK SYSTEMS

ANALYSIS

ENTRANCE AND EXIT SEPARATIONS.

The first part of the analysis focused on the variability in longitudinal separation in minutes between sequential same-route, same-direction, coaltitude aircraft pairs as they entered and exited from the CEP system. Interarrival times in minutes were tabulated for pairs of aircraft and were grouped according to route, altitude, and direction. It was decided for two reasons that 130W and 150W longitudes would be treated as the entrance and exit points on each of the four routes rather than using each route's gateways:

1. The data set is more complete for these longitudinal reporting times, and

2. Very often, on both ends of the CEP track system, aircraft are vectored off route under radar control before passing inbound gateways. This, too, depleted the data base available for investigation.

The tabulation of entrance and exit separations is summarized in table 1. Only aircraft pairs with initial separations up to 60 minutes are included, and route and altitude groupings have been collapsed into eastbound and westbound categories for ease of assimilation by the reader. The disparity between entrance and exit totals is attributed either to initial separations of less than 60 minutes swelling during flight beyond 60 minutes (and, therefore, not counted) or to initial separations greater than 60 minutes (and not counted) shrinking during flight to less than 60 minutes (and being counted). A more thorough set of tables can be found in appendix A where the altitude and route designations have been retained.

Reporting times and related altitude and route data for 7,724 eastbound and 8,754 westbound aircraft were deemed acceptable (table 2). The percentage of aircraft going eastbound or westbound mimics the original distribution almost exactly. No entrance separations less than 14 minutes, with the exception of less than five military pairs flying formation and providing their own separation (and, hence, not included in the tables), were found. Likewise, a scanning of the exit separations (table 1) reveals no interpair separations less than 9 minutes (except for the military pairs cited above, which again are excluded). This downward shift from a minimum entrance separation value of 14 minutes to a minimum exit separation of 9 minutes can be accounted for by the second aircraft travelling at a faster speed and closing the distance between itself and a slower plane ahead of it. This was precisely the case with the seven aircraft pairs on the exit tables which showed final separations less than 14 minutes.

FIRST CLASSIFICATION BY MACH NUMBER. A thorough, automated search of the FHF data was made to identify all same-route, same-direction coaltitude pairs in which the trailing aircraft was as fast or faster than the leading. This speed differential could be ascertained directly for the majority of pairs based on the mach number filed by, or assigned to an aircraft during its

TABLE 1. SUMMARY OF CEP ENTRANCE AND EXIT SEPARATIONS

Separation (Minutes)	Entrance: Eastbound Aircraft	Entrance: Westbound Aircraft	Exit: Eastbound Aircraft	Exit: Westbound Aircraft
9	0	0	0	1
10	0	0	0	0
11	0	0	0	0
12	0	0	1	0
13	0	0	1	2
14	1	2	0	2
15	10	9	17	26
16	37	33	33	24
17	34	33	35	32
18	48	45	45	47
19	64	59	46	44
20	71	61	60	58
21	68	68	72	58
22	82	71	69	53
23	68	69	66	53
24	73	55	76	56
25	70	82	70	68
26	75	67	90	56
27	70	66	86	79
28	59	59	69	66
29	53	74	68	80
30	62	63	43	74
31	57	57	55	63
32	65	58	51	61
33	46	49	56	50
34	58	62	63	59
35	64	56	42	75
36	57	59	68	56
37	58	59	55	60
38	53	52	39	55
39	47	53	55	53
40	57	44	36	46
41	52	46	51	46
42	52	57	64	49
43	42	44	47	47
44	50	61	34	44
45	45	58	44	63
46	45	53	58	51
47	36	46	48	43
48	40	55	51	44
49	46	29	36	46
50	36	52	45	42
51	47	43	41	38
52	26	32	38	46
53	36	45	37	53
54	35	41	34	48
55	43	46	45	54
56	43	49	38	52
57	36	36	36	43
58	43	40	40	41
59	45	43	42	38
60	49	45	34	36
TOTAL	2354	2396	2330	2381

NOTE: Eastbound entrance point = 150W, exit point = 130W
Westbound entrance point = 130W, exit point = 150W

flight. (A mach number is the ratio of an aircraft's speed to the speed of sound.) Those aircraft lacking a mach number were assigned one in this analysis according to their aircraft type. The assignment scheme is summarized in table 3 and is modeled after the most commonly observed mach speeds in the field for a particular aircraft type. Later in the analysis these mach speeds were used only to estimate expected changes in longitudinal separation.

TABLE 2. ANALYZED SAMPLE COMPARED TO COMPLETE FHF DATA SET

	Eastbound		Westbound		Total	
	Aircraft	Percent	Aircraft	Percent	Aircraft	Percent
Complete FHF Data Set	8,545	47.0	9,619	53.0	18,164	100
Analyzed Sample	7,724	46.9	8,754	53.1	16,478	100

TABLE 3. MACH NUMBER ASSIGNMENT SCHEME

B747	.84
DC10	.83
B720	.82
B707	.81
DC8	.80
C5A	.77
C141	.74
KC135	Variable**

**Varied with altitude, approximately equal to 450 knots true airspeed (TAS).

Of the 16,478 aircraft available for analysis, 2,850 pairs were identified in which the trailing aircraft was as fast as or faster than the lead, and all pairs were categorized according to the difference in mach number between them. Mach speeds in the CEP range between .72 and .86, but so few aircraft flew below .74 or above .84, that no examples were found for mach speed differences greater than .10 (and even the .10 group had only 34 members). No pairs with initial separation greater than 60 minutes were included in the 2,850.

The results of this classification are presented in tables B-1 to B-16 in appendix B. Each table categorizes the aircraft pairs for the specified mach number difference and direction by their initial separation and change in separation enroute. Thus, in table B-1, of the five aircraft pairs separated initially by 15 minutes at 150W longitude, two pairs arrived over 130W separated by 15 minutes (i.e., initial separation plus zero minutes), two by 17 minutes (initial plus 2), and one by 18 (initial plus 3).

SECOND CLASSIFICATION BY MACH NUMBER. Having generated the aforementioned distributions of same speed or faster aircraft in the rear, a second identical classification was made of those same-route, same-direction, coaltitude pairs in which the second aircraft was slower than the first. An additional 1,856 pairs were identified which met this criterion, for a grand total of 4,706 pairs. Again, the scheme of table 3 was used for assigning mach speeds to those aircraft which lacked one. The results of this second classification are presented in the second half of appendix B, tables B-17 to B-30.

SEPARATION CHANGES AND MACH NUMBER SPACING.

Further understanding of longitudinal spacing in the CEP can be gained from closer scrutiny of the changes in separation. However, it is not enough merely to state that an aircraft pair's separation changed from 25 minutes initially to 21 minutes on exit, for example. If both aircraft were flying the same mach speed, this result is somewhat surprising, since one would not expect the second plane to gain on the first. If, on the other hand, the trailing plane was flying a mach speed greater by .02 mach, a closing of the separation by 4 minutes would be expected for the route lengths involved (130W to 150W). Any investigation of changes in longitudinal separation, therefore, should take into account the expected shrinkage of separation owing to the disparity of aircraft speeds (or lack of disparity). Such an adjustment would give a more accurate estimation of the ability of the two aircraft to fly a constant mach speed and thereby enabling use of mach-speed separation techniques.

Consequently, for the study of separation changes, the actual observed time change, T_c (i.e., exit separation minus entrance separation), was adjusted by the expected change in separation, T_e, based on route length and on difference in true groundspeeds. (The groundspeed is a function of mach speed, adjusted for wind and temperature.) This yielded for the ith aircraft pair a change in separation, T_i, defined by the relation:

$$T_i = T_o - T_e$$

T_i, then, is the change in longitudinal separation adjusted for mach speed differences; i.e., seemingly random changes incurred by various other or unknown factors.

Histograms of the T_i's were generated for the 4,706 aircraft pairs mentioned earlier and for numerous partitions of this grand total. Figure 2 presents the changes in longitudinal separation for all 4,706 pairs of aircraft over a range of mach speed differences from -.10 to +.10. The distribution is nearly symmetrical, ranges in value from -15 to +17 minutes, and has a near-zero mean of .080 minutes and a standard deviation of 3.08 minutes. Just under half of the data, 45.3 percent, is bunched into the -1, 0, and +1 columns. A plot of the cumulative distribution on normal probability paper appears in figure 3. The nonlinearity of the resultant curve leads to the conclusion that the distribution is not normal, and a chi-square χ^2 goodness of fit test

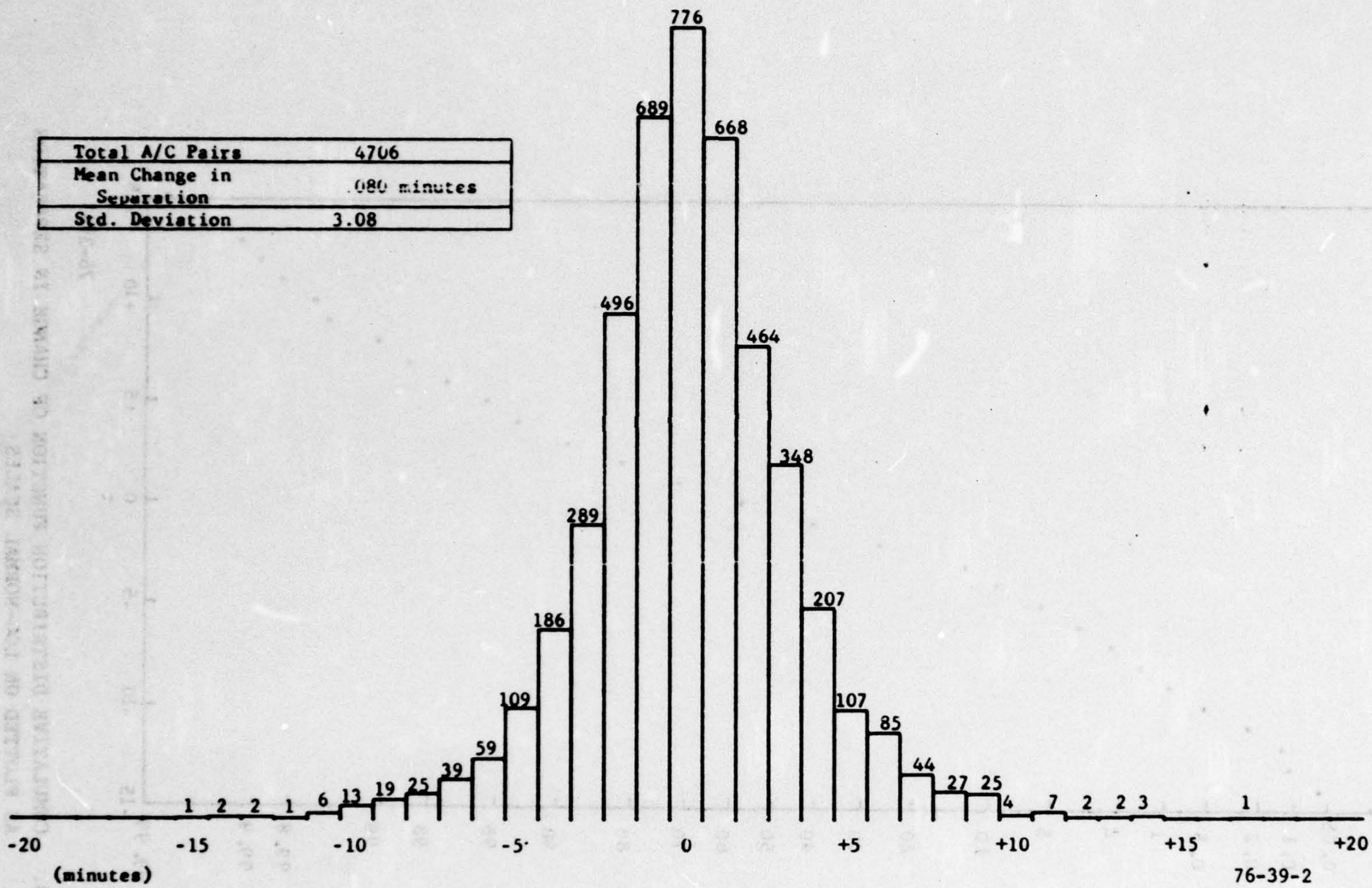


FIGURE 2. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF -.10 THROUGH .10, EAST AND WESTBOUND TRAFFIC

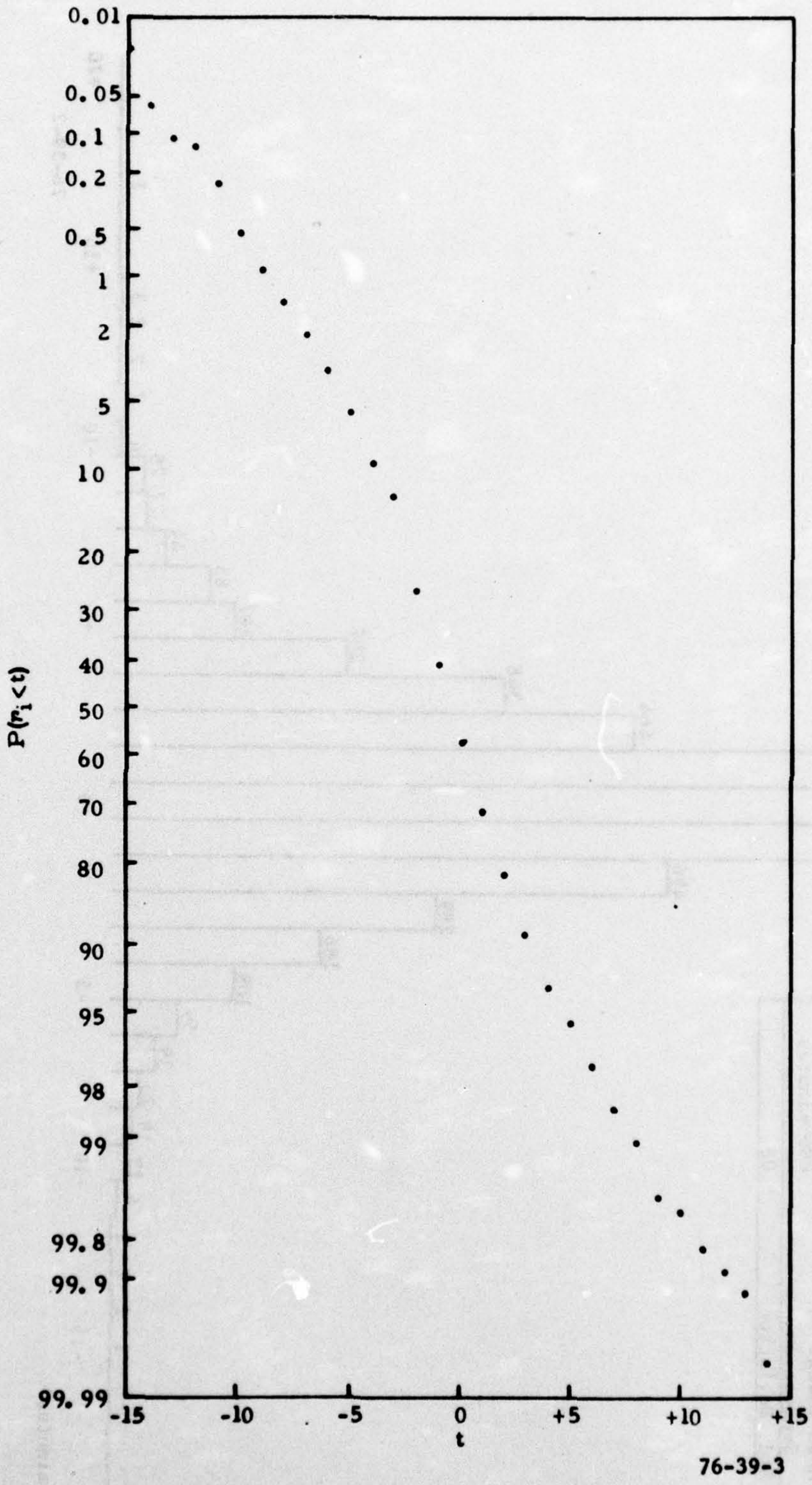


FIGURE 3. CUMULATIVE DISTRIBUTION FUNCTION OF CHANGE IN SEPARATION AS PLOTTED ON LOG-NORMAL SCALES

against a normal distribution with N = 4,706 and s = 3.08 also failed to confirm normality. The critical χ^2 value of 37.5 (p = .99, df = 20) is far exceeded by the empirically determined value of 373.15.

Appendix C to this report presents a breakdown of the 4,706 changes in separation grouped according to the mach speed difference between the two aircraft in the pairs. Histograms for same-speed pairs (mach difference = 0), fast-following-slow pairs (difference = .01 to .10), and slow-following-fast pairs (difference = -.01 to -.10) can be found there.

The 4,706 changes in longitudinal separation were divided into two groups: (1) the 3,293 same-route, coaltitude pairs in which both aircraft filed or were assigned a mach number in the field, and (2) the 1,413 pairs in which one or both aircraft lacked a mach number. The resultant histograms are presented in figures 4 and 5.

A comparison of the "nonmach" distribution of 1,413 pairs with the "mach-only" distribution of 3,293 pairs reveals that both are distributed over a very similar range of values: ± 15 minutes, except for a single pair at 17 minutes in figure 5. The mean values differ by only .098 minutes (i.e., 6 seconds). The measures of skewness are .063 for the mach-only and -.022 for the nonmach, indicating that both distributions are quite nearly symmetrical.

Visually, the mach-only histogram appears more pointed around zero, a conclusion which is slightly supported by the measures of kurtosis (1.88 as compared to 1.537 for the nonmach). (Kurtosis, or the fourth moment, is one measure of distortion of a normal distribution, a greater or lesser value reflecting a greater or lesser "peakedness" to the distribution.) However, a greater bunching about the center of the mach-only data is more strongly confirmed by the smaller standard deviation, 2.91, for the mach-only pairs compared to the 3.45 for nonmach. Calculations of mean, standard deviation, skewness, and kurtosis all provide quantitative indications of the differences between the two distributions. Still another comparison is possible in figures 6 and 7, which are relative frequency histograms of the two data sets. This provides comparability of scaling, since the height of any spike represents the percentage of the entire distribution found in that column. The greater concentration of the mach-only data about the center reveals itself most clearly in a visual comparison of these two graphs. Also to be noted is the greater percentage of the nonmach data dispersed into the tail areas, perhaps suggesting a decreased capability of nonmach aircraft in maintaining longitudinal separation. This will be covered in more detail below.

Since the mach-only and nonmach distributions differ in the ways noted above, the question ultimately arises as to whether these differences are statistically significant. Are both data sets so similar that it can be said that all members were drawn from the same population, and, therefore, that they all maintain longitudinal separation equally well or poorly? Or are these two distributions different enough to conclude that their members' respective abilities to maintain separation also differ significantly? In an attempt to answer these questions, a statistical analysis was done which led to the following conclusions:

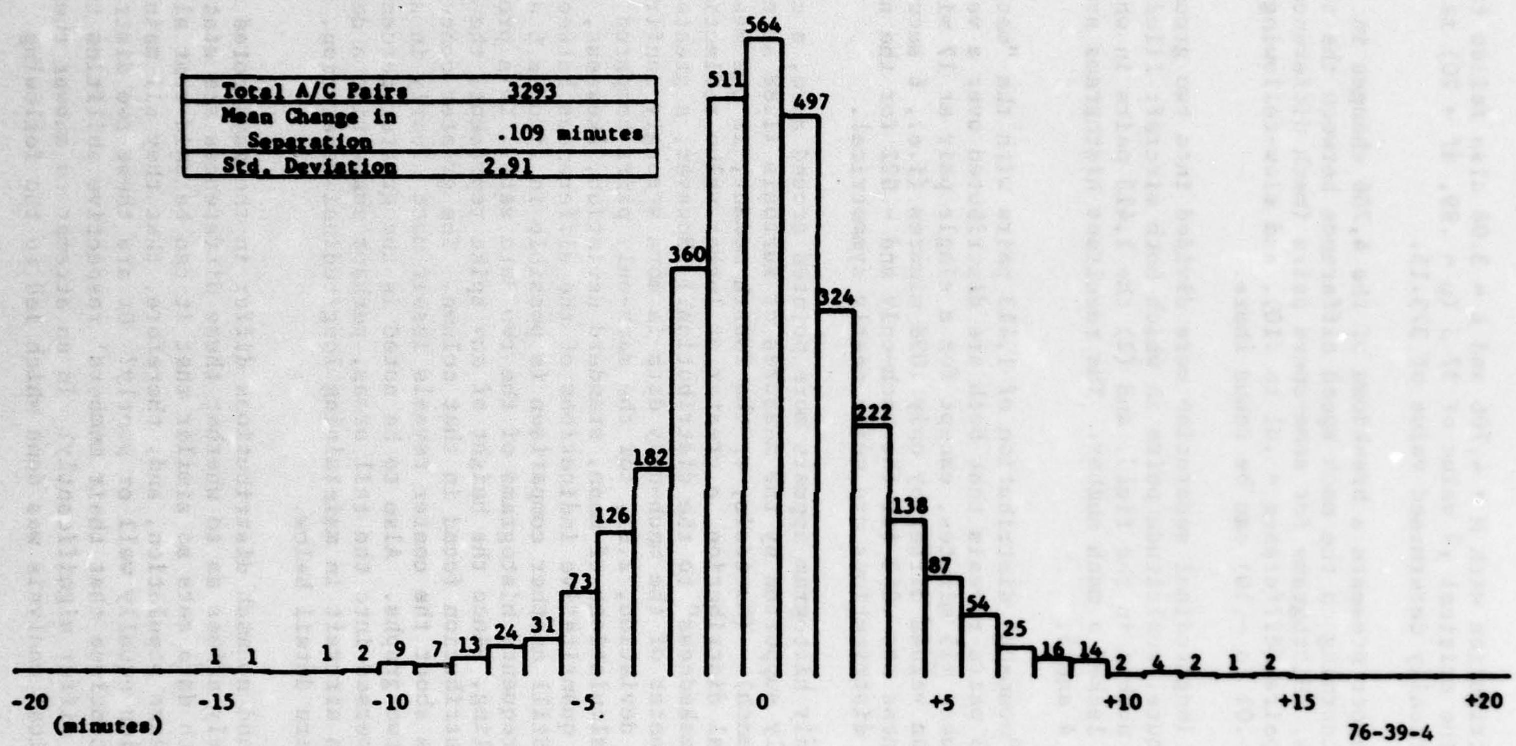


FIGURE 4. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED MACH NUMBER DIFFERENCES OF -.10 THROUGH .10, EAST AND WESTBOUND TRAFFIC

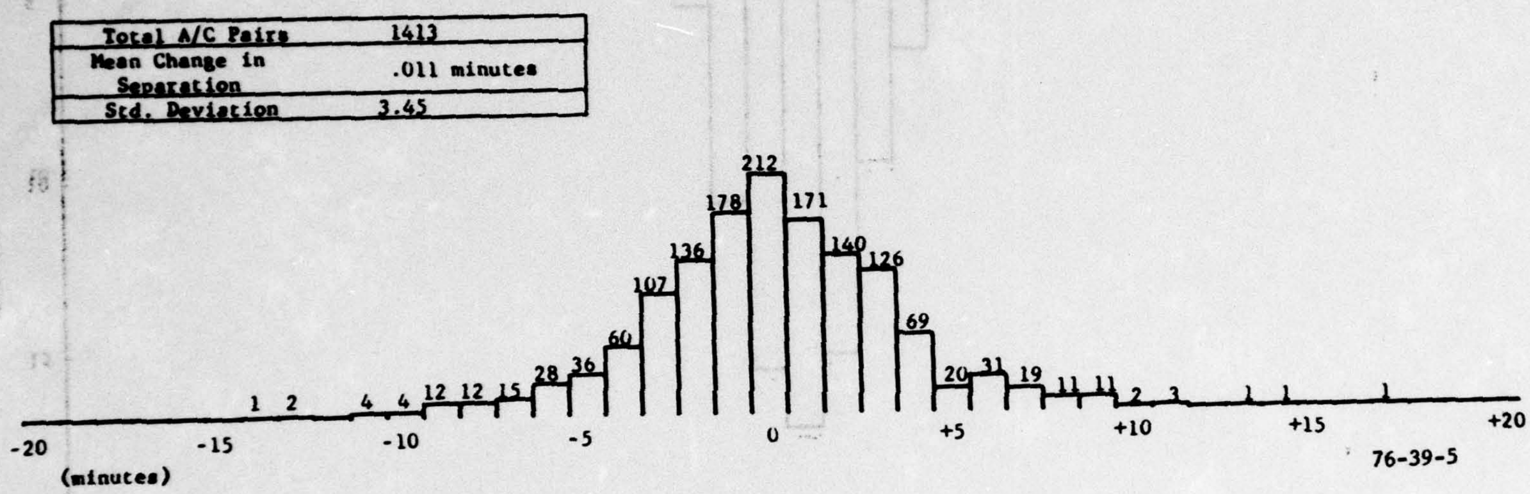


FIGURE 5. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH ESTIMATED MACH NUMBER DIFFERENCES OF -.10 THROUGH .10, EAST AND WESTBOUND TRAFFIC

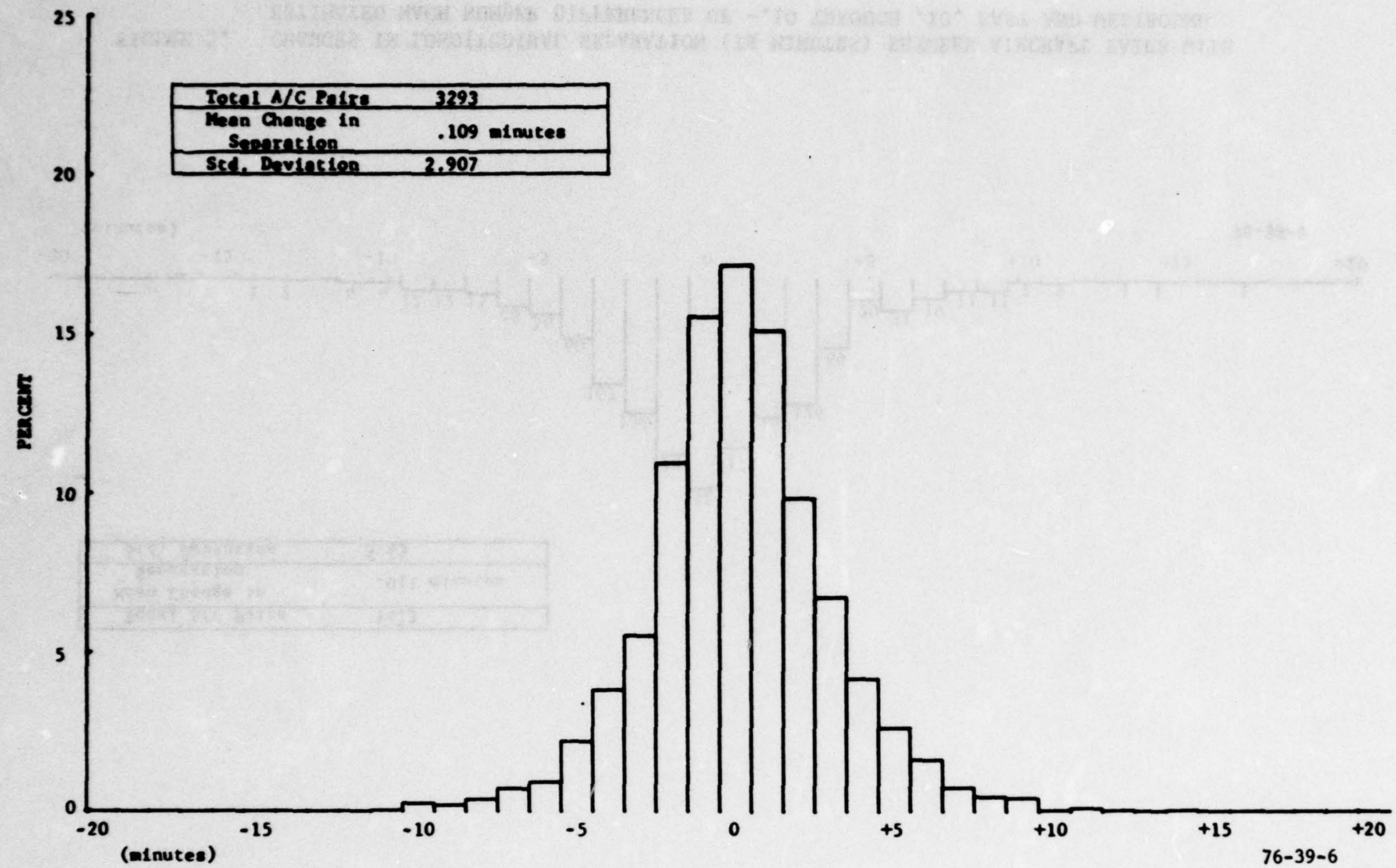


FIGURE 6. RELATIVE FREQUENCY HISTOGRAM OF MACH-ONLY CHANGES IN LONGITUDINAL SEPARATION, EAST AND WESTBOUND TRAFFIC

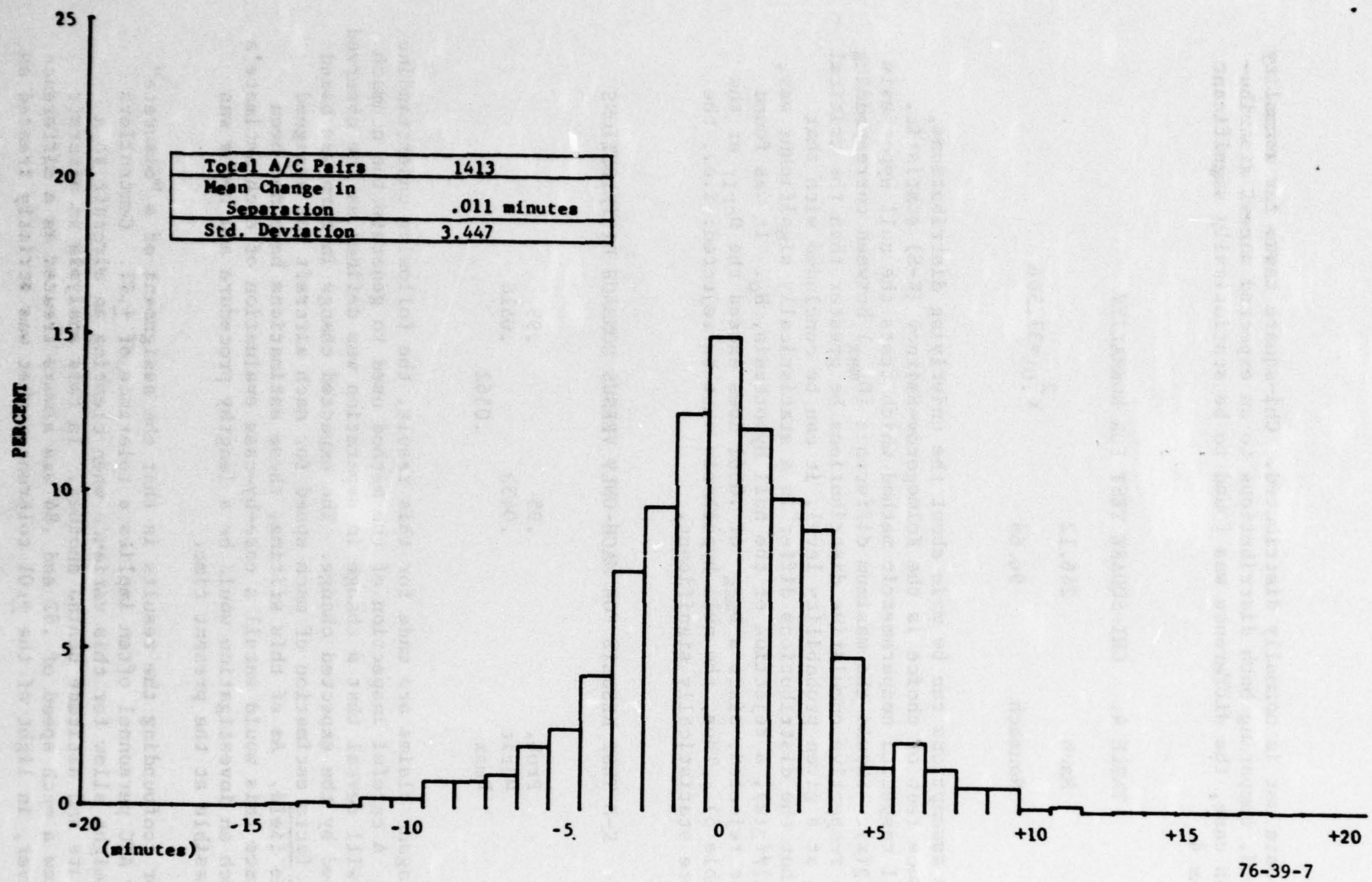


FIGURE 7. RELATIVE FREQUENCY HISTOGRAM OF NONMACH CHANGES IN LONGITUDINAL SEPARATION, EAST AND WESTBOUND TRAFFIC

1. Neither data set is normally distributed. Chi-square tests for normality were calculated, comparing both distributions to an expected normal distribution. In each case, the difference was found to be statistically significant ($p \geq .99$), table 4.

TABLE 4. CHI-SQUARE TEST FOR NORMALITY

Mach	246.12	$\chi^2_{.01}=37.566$
Nonmach	96.66	

2. Since no assumptions can be made about the underlying distributions, the significance test of choice is the Kolmogorov-Smirnov (K-S) statistic. This is a well respected nonparametric method which tests the null hypothesis H_o: $f_1(x) = f_2(x)$. Should the maximum difference (D_{max}) between corresponding spikes of the respective cumulative distributions be greater than the critical value (D_{crit}) at a given probability level, it can be concluded with that probability that the distributions differ in a statistically significant way, that is, $f_1(x) \neq f_2(x)$, a rejection of the null hypothesis, H_o. It was found that H_o can be rejected, since a D_{max} of .0562 does exceed the D_{crit} at the .99 level (table 5). Thus, the null hypothesis must be rejected; i.e., the differences are statistically significant.

TABLE 5. K-S TEST RESULTS FOR MACH-ONLY VERSUS NONMACH DISTRIBUTIONS

Prob.	.95	.99
D_{crit}	.0433	.0518
D_{max}	.0562	

Before extravagant claims are made for this result, the following understanding is necessary. A careful inspection of the method used to generate the nonmach distribution will reveal that a change in separation was defined as the observed change adjusted by the expected change. The expected change in turn was based on an <u>ex post facto</u> estimation of mach speed for each aircraft not assigned a speed in the field. As of this writing, these estimations have not been validated, since this would entail a case-by-case evaluation of each estimate's accuracy. Such an investigation would be a lengthy procedure and hence was not deemed feasible at the present time.

Another factor confounding the results is that the assignment of a "discrete" mach speed by ATC personnel often implies a tolerance of $\pm.01$. Controllers consequently might allow for this variance when clearing an aircraft to a particular route and altitude behind another. In this analysis an aircraft pair which flew a mach speed of .82 and .84 was always treated as a difference of .02. However, in light of the $\pm.01$ tolerance, what was strictly treated as

a .02 difference may have varied from .00 to .04 with attendant variations in expected changes in separation.

Therefore, the reader is free to conclude that the ability of the mach-only aircraft pairs to maintain longitudinal separation differs a statistically significant amount from nonmach pairs, provided he keep in mind the following two conditions of this analysis:

1. The "true" nonmach distribution may be obscured by systematic errors in the *ex post facto* estimation of mach speeds for nonusers.

2. The mach-only distribution was generated without considering the de facto ±.01 deviation of certain users from their assigned mach number speed.

WORST-CASE NOMOGRAPH.

As noted above, mach-speed assignments can vary within ±.01 of the actual value assigned. As a result of this variability, the actual difference in mach speeds between any two aircraft might diverge as much as ±.02 from the apparent difference. For instance, an apparent difference of .02 between a pair flying .83 and .85 mach might in reality be any of the following speeds: .84 and .86, .84 and .85, .84 and .84, .83 and .86, .83 and .85, .83 and .84, .82 and .86, .82 and .85, or .82 and .84, with respective mach speed differences of .02, .01, 0, .03, .02, .01, .04, .03, and .02. If in fact the extreme of .04 were the *actual* difference, the expected change in longitudinal separation would be greater than the posted .02 difference would predict. A series of such "worst-case" expectations of change (loss) in separations, assuming no controller intervention, has been developed for various apparent mach differences (0 to +.10) and over various mileages (0 to 2,000 nautical miles (nmi)), and is presented in the nomograph of figure 8. It is hoped that this will prove a convenient instrument for future route planners, who will need to allow for changes in longitudinal separation.

The method used to predict expected separation changes followed the established National Airspace System (NAS) algorithm for converting mach speeds to true airspeeds (TAS), reference 2. For convenience in the calculation, all aircraft were assumed to be flying at a median altitude of 35,000 feet, allowing, therefore, a single, discrete speed in knots for each mach number (since a given mach number will have different speed at different altitudes). Dividing this speed into a specified route length (e.g., 2,000 nmi) yielded a trip time for each speed, and computing the difference in trip times between any two speeds produced the expected separation change. Finally, these changes were grouped according to the mach difference (0 to +.10) of the aircraft pair.

USING THE NOMOGRAPH. 1. Locate along the x-axis the route distance for which a change in longitudinal separation is desired. 2. Locate in the right-hand margin the mach difference for which a worst-case prediction is desired. This number will be associated with a line originating at zero. 3. Trace vertically from the chosen x-axis mileage to its intersection with the mach-difference line. Trace horizontally left to the y-azis and read a value (in minutes) for worst-case expected change.

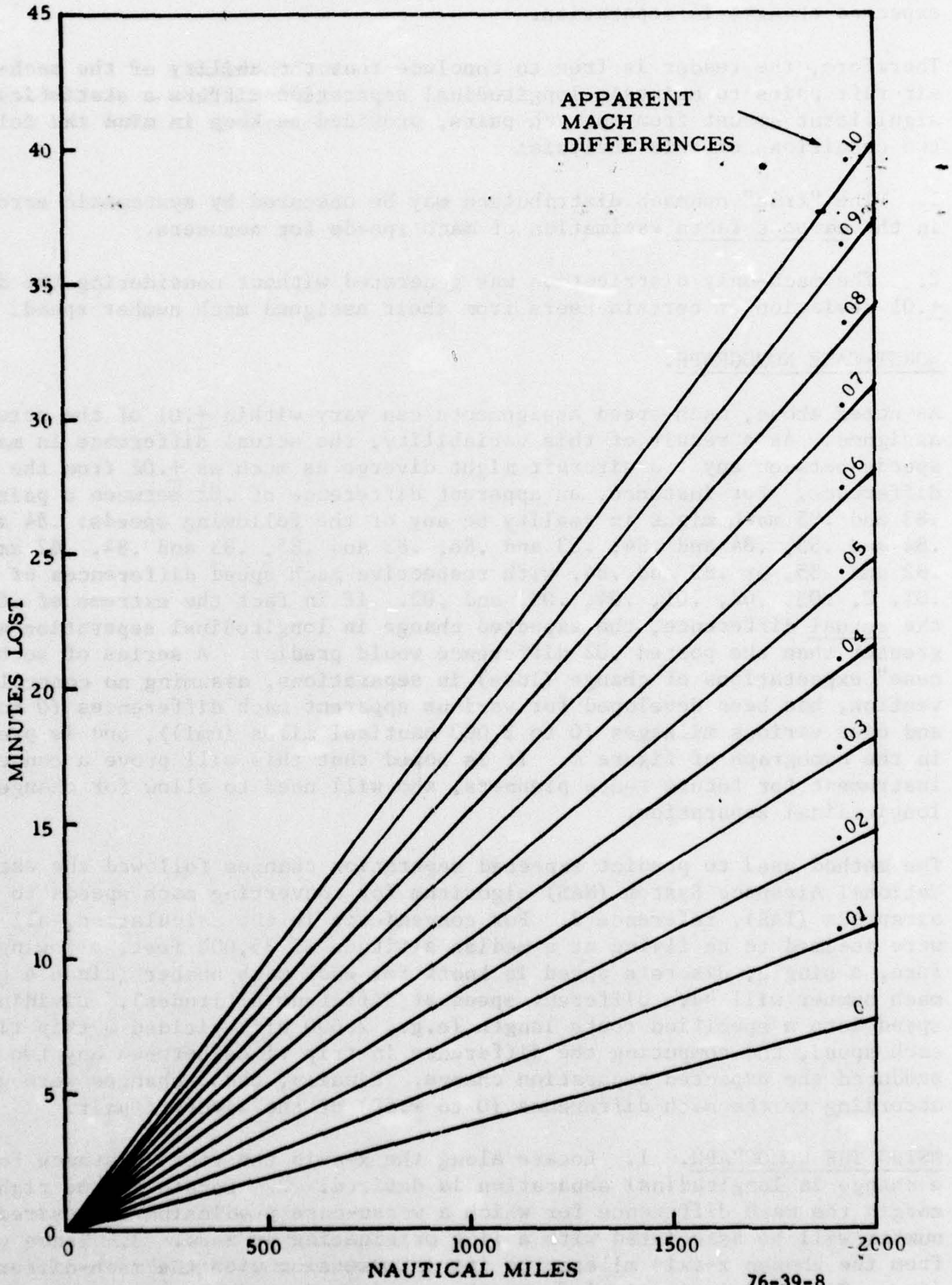


FIGURE 8. WORST-CASE CHANGES IN LONGITUDINAL SPACING (ALTITUDE 35,000 FEET)

For instance, how many minutes maximum would a .84 mach aircraft be expected to gain on a .83 over 1000 nmi? Apparent speed difference is computed by subtracting the leading aircraft's speed from the trailing, in this case +.01. Trace straight up from 1000 along the x-axis until the .01 line is intersected; trace straight left from this point, intersecting y-axis near 6 minutes. Answer: maximum expected loss of separation is 6 minutes.

SEPARATION CHANGES AND INS.

In the minutes of the ninth meeting of NAT/SPG (reference 3), the Canadian member reported a significant difference between the respective abilities of INS-equipped and non-INS-equipped aircraft in maintaining along-track separation. A similar analysis was performed on the CEP data to verify or refute this finding for the CEP track system.

The CEP data collection included information for roughly 60 percent of the flights as to whether an aircraft was navigating through the use of INS or some other mode. The unknown 40 percent were assumed to be INS-equipped if wide-bodied and not INS-equipped if narrow-bodied. It was recognized that some narrow-bodied aircraft, in fact, navigate with INS and, hence, would be assumed incorrectly to be non-INS-equipped. However, any bias this navigation equipment assignment scheme introduced would most likely serve to minimize the effect of INS on longitudinal separation, since the overall performance of the non-INS group would be owed in part to its wrongly assigned INS members and since any potential difference between the two groups might, thereby, be obscured. The assignment scheme, consequently, is a conservative one. The same distribution of 4,706 changes in longitudinal separation was broken into three groups, according to the navigation equipment of the aircraft pair. The three groups were:

1. Those where both aircraft of the pair were INS-equipped (INS-INS),

2. Those where only one aircraft of the pair was INS-equipped (INS-OTHER), and,

3. Those where neither aircraft was INS-equipped (OTHER-OTHER).

The three distributions are presented in figures 9, 10, and 11. The histograms show the greatest bunching of separation changes in the INS-INS group, where over half (55 percent) of the changes were -1, 0, or +1 minute. This compares to 42 percent for the INS-Other and 38 percent for Other-Other. The same trend is reflected in the respective variances, also, 6.56 (INS-INS), 9.91 (INS-Other), and 12.37 (Other-Other). These variances were all found to differ significantly ($p \geq .99$) from one another when compared in an F-ratio test. With such large sample sizes, an $F \geq 1.11$ is significant at the 0.01 level for all three comparisons. As can be seen in table 6, all F values far exceed the critical value of 1.11. Finally, K-S tests between the groups determined that all three differ significantly, too ($p = .99$) (table 7). Consequently, this analysis of the data led to the conclusion that the more INS-equipped aircraft existing in a given sample, the better that sample's ability at maintaining longitudinal separation.

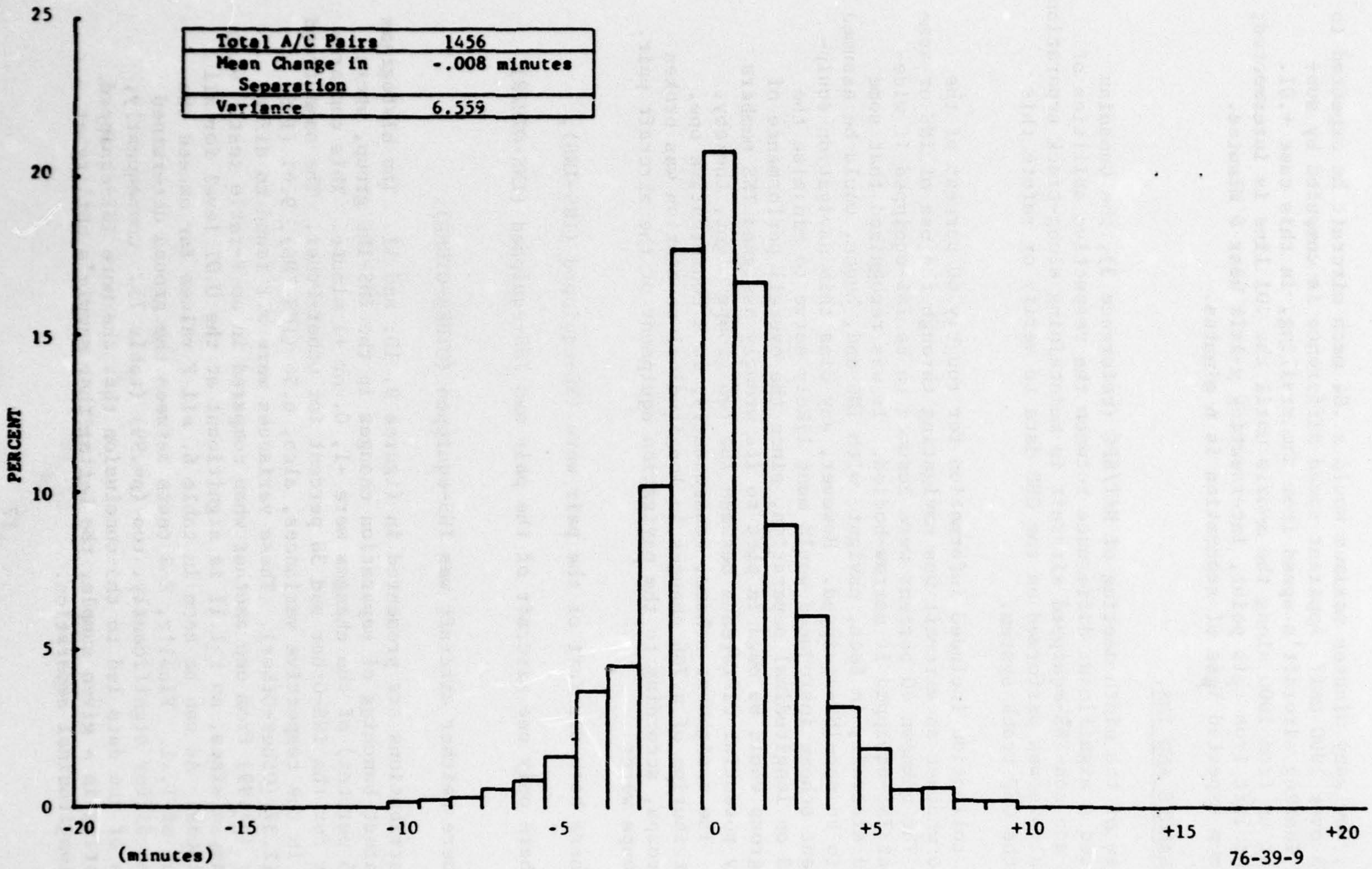


FIGURE 9. RELATIVE FREQUENCY HISTOGRAM OF INS-INS CHANGES IN LONGITUDINAL SEPARATION, EAST AND WESTBOUND TRAFFIC

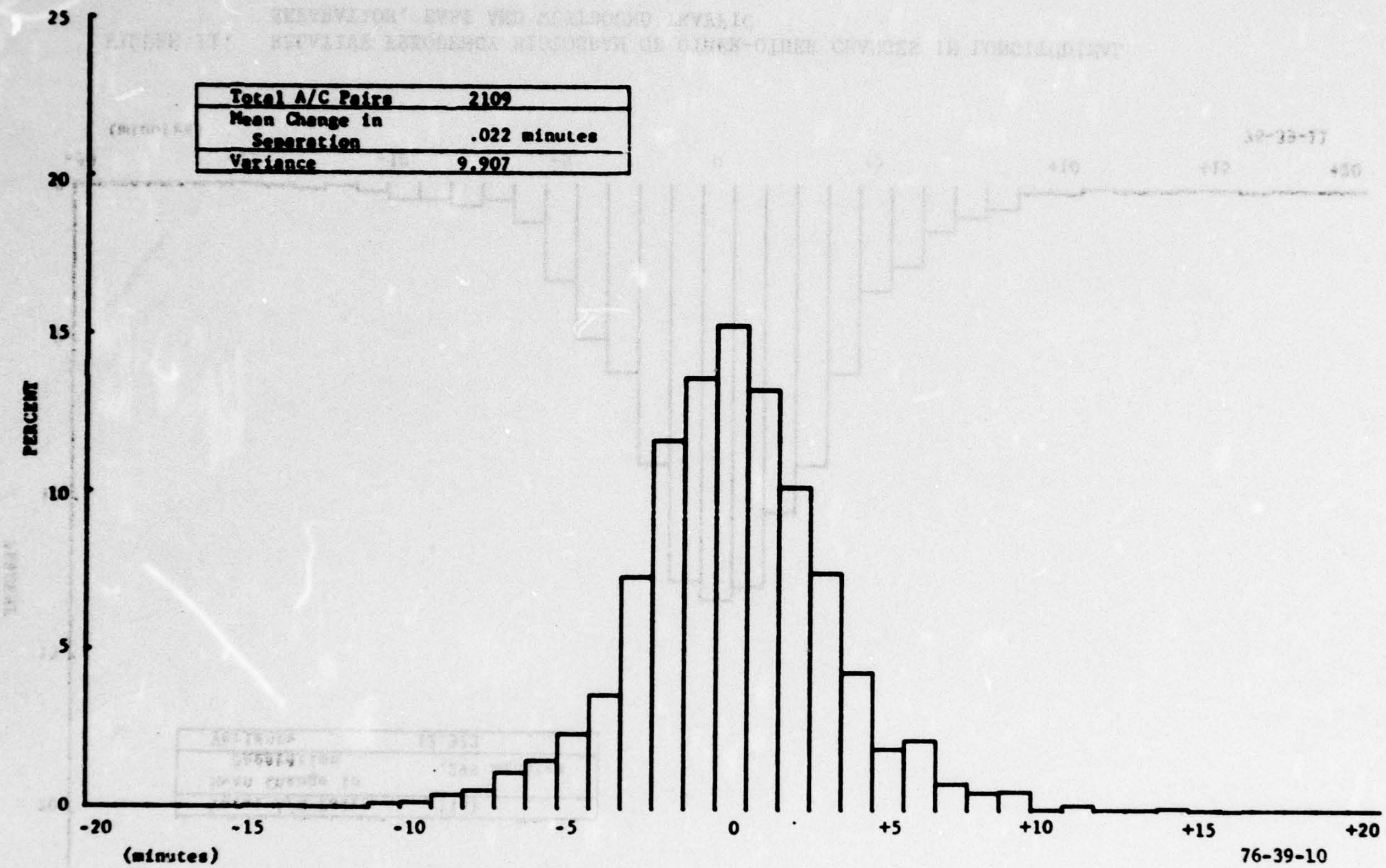


FIGURE 10. RELATIVE FREQUENCY HISTOGRAM OF INS-OTHER CHANGES IN LONGITUDINAL SEPARATION, EAST AND WESTBOUND TRAFFIC

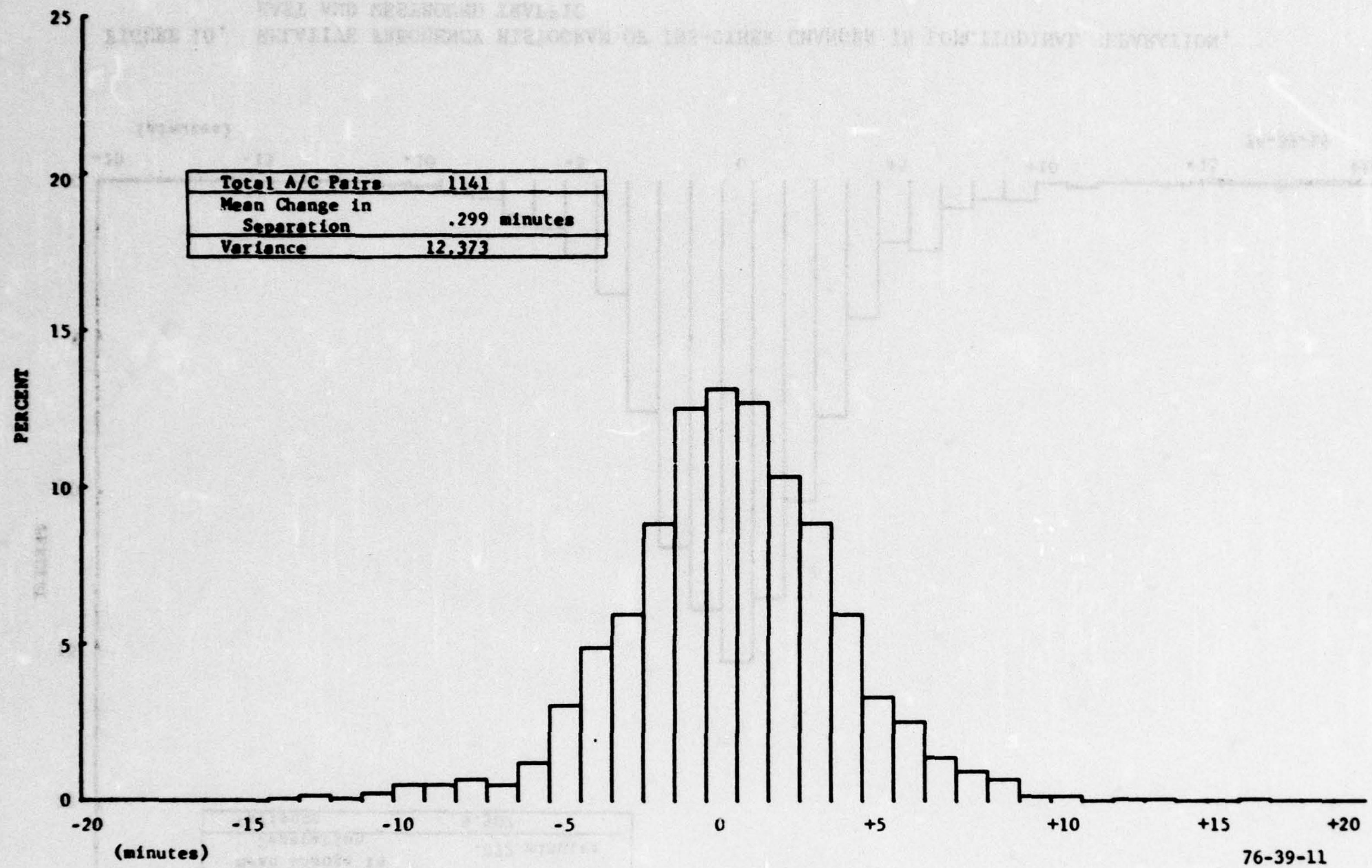


FIGURE 11. RELATIVE FREQUENCY HISTOGRAM OF OTHER-OTHER CHANGES IN LONGITUDINAL SEPARATION, EAST AND WESTBOUND TRAFFIC

TABLE 6. F-RATIO TEST RESULTS FOR NAVIGATION GROUPINGS

Other-Other	versus	INS-Other	1.25
Other-Other	versus	INS-INS	1.89
INS-Other	versus	INS-INS	1.51

TABLE 7. K-S TEST RESULTS FOR NAVIGATION GROUPINGS

Differences Distributions Compared	$D_{.05}$	$D_{.01}$	Dmax
INS-INS vs. INS-Other	.0463	.0555	.0661
INS-INS vs. Other-Other	.0538	.0644	.1239
INS-Other vs. Other-Other	.0500	.0599	.0602

The question immediately arises as to why the improved track-keeping ability of INS aircraft (i.e., fewer and smaller lateral deviations) should also be accompanied by improved maintenance of longitudinal separation. Although a conclusive answer to this question was not found, a number of possibilities were explored and several were rejected as plausible explanations. Possible causative factors fell into two categories, (1) data treatment effects and (2) physical phenomena effects.

Regarding data treatment effects, there existed the possibility that a systematic error was introduced in adjusting for mach number differences. To confirm or deny this, a brief analysis was done of those aircraft pairs for which no mach number adjustment was necessary in calculating the change in separation (i.e., those pairs with a mach difference of zero). In no case were the nonadjusted distributions found to differ significantly from the adjusted. The mach number adjustment scheme, therefore, appears valid. As pointed out in the section above on mach number spacing, however, the ex post facto estimation of mach speeds for those aircraft not assigned one in the field and the de facto ±.01 deviation of certain users from their assigned mach speed could significantly alter the structure of the distributions involved, but it is doubtful that such alterations could be large enough to offset the pronounced differences between the three navigation groupings.

Possible physical explanations include the fact that those aircraft with INS are predominately more modern, high-performance aircraft with more sophisticated autocoupling, flight computers, flight control stabilization techniques, and other factors leading to better (tighter) control dynamics. Thus, the reader should not attribute any of the differences in the arbitrary assignment of an

INS category as implying that INS of itself is sufficient to explain a cause and effect relationship. In fact, these differences are probably an artifact of the data due purely to the artificial classification by navigation equipment, dictated by the constraints of the data available in the FHF.

In summary, significant differences in longitudinal spacing changes were found for INS-INS aircraft pairs versus INS-Other pairs versus Other-Other pairs. The exact cause of these differences is uncertain, but the differences are clearly statistically significant and operationally meaningful in the CEP data.

LONGITUDINAL COLLISION RISK.

NAT/SPG DISCREPANCY. In calculating the collision risk due to the loss of longitudinal separation, the collision risk model of the North Atlantic Systems Planning Group (NAT/SPG) was employed, following the procedures described in the minutes of the fifth NAT/SPG meeting (reference 4). Using this approach, a longitudinal risk on the order of .537 accidents per 10 million flying hours was calculated for the CEP. Since this result is beyond the target level of safety (.2 to .4) accepted in the North Atlantic Organized Track System, a more detailed analysis of the NAT/SPG longitudinal collision risk model was initiated.

The NAT/SPG model is given by the following equation:

$$N_{ax} = 2x10^7 \left[\frac{\overline{|\dot{x}|}}{2\lambda_x} + \frac{\overline{|\dot{y}(0)|}}{2\lambda_y} + \frac{\overline{|\dot{z}(0)|}}{2\lambda_z} \right] P_y(0)\ P_z(0)\ \pi_x$$

where $\pi_x = \dfrac{4\lambda x}{V_x/60} \quad \Sigma E_x(t)_{Px}(t)$ $\quad P_x(t)$ = probability that a pair looses exactly t minutes

As a first approach, a separate risk model was derived in order to approximate the collision risk through an independent analysis. This method, more fully documented in appendix D, yielded a final value of .0166 accidents in 10 million flying hours. This result, being so vastly different from the NAT/SPG V approach, led to a more in-depth study of longitudinal collision risk.

Review of the literature (reference 5 and 6) describing the model's derivation reveals that π_x is the proportion of time the aircraft spend adjacent or passing one another. However, in the minutes of the NAT/SPG V meeting, π_x was taken only to be the probability of occurrences of aircraft in collision proximity. Consequently, an appropriate conversion was made such that

$$\pi_x = \frac{2\lambda_x \quad \Sigma E_x(t)\ P_x(t)}{\overline{|\dot{x}|}\ (\bar{T})}$$

Definition of the model's parameters and their respective values are given in table 8 except for the $E_x(t)$ and $P_x(t)$ distributions. An important difference between these parameters and those of NAT/SPG V is the magnitude of the along-track relative speed $\overline{\dot{x}}$. In the present risk calculation, $\dot{x}$ was conservatively chosen at 49.33 knots instead of 26 knots, since the former represents the average velocity differential only for those aircraft that catch up or pass, while the latter is the average for all aircraft.

TABLE 8. LONGITUDINAL COLLISION-RISK PARAMETERS

	Parameter	Value
$P_y(0)$	Probability of Lateral Overlap of Same-Route Pair	0.0033
$P_z(0)$	Probability of Vertical Overlap of Same-Route Pair	0.25
λ_x	Aircraft Length	0.033 nmi
λ_y	Aircraft Wingspan	0.033 nmi
λ_z	Aircraft Height	0.0085 nmi
$\lvert\overline{\dot{x}}\rvert$	Minimum Along-Track Relative Speed Needed to Gain L_x Minutes	49.33 knots
$\overline{\lvert\dot{y}(0)\rvert}$	Average Relative Crosstrack Speed	20 knots
$\overline{\lvert\dot{z}(0)\rvert}$	Average Relative Vertical Speed	1 knot
L_x	Longitudinal Separation Minimum	15 minutes
$\overline{V}_x$	Average Along-Track Velocity	480 knots
$\overline{D}$	Average Track Length (130W to 150W)	1,163 nmi
$\overline{T}$	Average Flight Time (130W to 150W)	2.42 hrs (i.e., 145 min)

$E_x(t)$. Another important input to the risk calculation is the distribution of "effective" initial longitudinal separations, $E_x(t)$, figure 12, also expressed as a probability density function of time, t, in table 9. $E_x(t)$ was drawn from the 16,478 aircraft mentioned above, where it was also noted that there were no initial separations less than 14 minutes (table 1). However, it should be noted that figure 12 and table 9 show two aircraft pairs initially separated by 12 minutes. This apparent contradiction of the earlier 14-minute initial separation is no contradiction at all, because the latter distribution actually represents the effective initial separations. It was reasoned that any initial separation between two aircraft, in fact, masked their "true" separation, since ATC allows extra spacing between them in anticipation of changes in their separation enroute. For instance, a B747 that was 18 minutes behind a C141 could be thought of as more closely spaced than a C141 separated by 18 minutes behind a B747, since a B747 is very likely to gain on a C141 but not the reverse. Yet simply to categorize each case as an 18-minute separation would conceal their differences in expected change in separation. In order to remove any such hidden disparities, an effective initial distribution was produced by subtracting the expected changes in separation enroute from the actual initial separation. This conservative adjustment resulted in three aircraft pairs appearing below the 14-minute minimum cited before.

TABLE 9. $E_x(t)$: DISTRIBUTION OF EFFECTIVE INITIAL LONGITUDINAL SEPARATIONS AS A FUNCTION OF TIME (N=16,478)

Effective Initial Separation (minutes)	Frequency (A/C Pairs)	$E_x(t)$
12	2	.00012
13	1	.00006
14	6	.00036
15	27	.00164
16	52	.00316
17	71	.00431
18	90	.00546
19	101	.00613
20	135	.00819
21	119	.00722
22	138	.00837
23	148	.00898
24	132	.00801
25	130	.00789
26	153	.00929
27	134	.00813
28	126	.00765
29	135	.00819
30	125	.00759

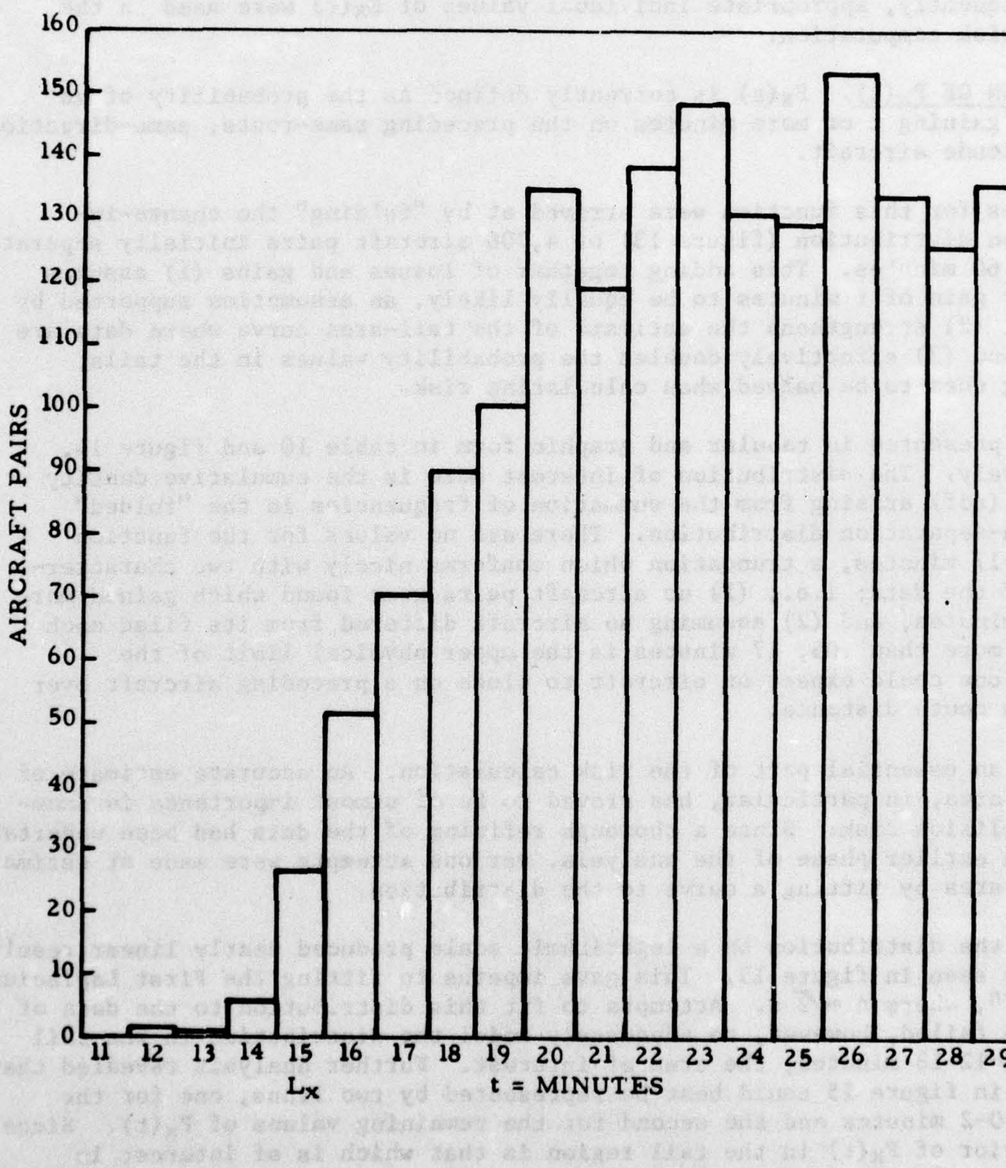


FIGURE 12. $E_x(t)$: EFFECTIVE INITIAL LONGITUDINAL SEPARATIONS OF SAME-ROUTE, COALTITUDE AIRCRAFT PAIRS

$E_x(t)$ extends beyond the 30 minutes shown in the table, but such values were unneeded in this analysis. The magnitude of $E_x(t)$ rises quickly from t=12 until t=23, after which point the distribution tends to decrease slowly in value. NAT/SPG V assumed that the value of $E_x(t)$ was at a maximum at t=15, and therefore, that E_x (15) could conservatively be substituted for all values of $E_x(t)$ in the risk calculation. The CEP data failed to support this assumption, and consequently, appropriate individual values of $E_x(t)$ were used in the current risk computation.

ESTIMATION OF $P_x(t)$. $P_x(t)$ is currently defined as the probability of an aircraft gaining t or more minutes on the preceding same-route, same-direction, same-altitude aircraft.

The values for this function were arrived at by "folding" the change-in-separation distribution (figure 13) of 4,706 aircraft pairs initially separated by up to 60 minutes. This adding together of losses and gains (1) assumes a loss or gain of t minutes to be equally likely, an assumption supported by the data, (2) strengthens the estimate of the tail-area curve where data are scarce, and (3) effectively doubles the probability values in the tails, requiring them to be halved when calculating risk.

$P_x(t)$ is presented in tabular and graphic form in table 10 and figure 14, respectively. The distribution of interest here is the cumulative density function (cdf) arising from the summation of frequencies in the "folded" change-in-separation distribution. There are no values for the function beyond t=17 minutes, a truncation which conforms nicely with two characteristics of the data; i.e., (1) no aircraft pairs were found which gained more than 17 minutes, and (2) assuming no aircraft differed from its filed mach speed by more than .05, 17 minutes is the upper physical limit of the distance one could expect an aircraft to close on a preceding aircraft over the given route distance.

$P_x(t)$ is an essential part of the risk calculation. An accurate estimate of the tail area, in particular, has proved to be of utmost importance in examining collision risk. Since a thorough refining of the data had been undertaken during an earlier phase of the analysis, various attempts were made at estimating the tail area by fitting a curve to the distribution.

Plotting the distribution on a logarithmic scale produced nearly linear results, as can be seen in figure 15. This gave impetus to fitting the First Laplacian cdf, $e^{-t/\eta}$, where $\eta = \sqrt{2}\,\sigma$. Attempts to fit this distribution to the data of figure 15 failed, however, to adequately model the distribution in the tail region, t=12-18 minutes, the area of interest. Further analysis revealed that the data in figure 15 could best be represented by two lines, one for the region t=0-2 minutes and the second for the remaining values of $P_x(t)$. Since the behavior of $P_x(t)$ in the tail region is that which is of interest in collision risk, effort was concentrated on determining the best parameter estimates for the model ae^{bt} in the region t=3-18 minutes. The exponential function resulting from the least squares linear fit is shown in figure 16, and the mathematical form of the model, describing the data of interest in figure 15 with a sample correlation coefficient of -.9958, is given by the following:

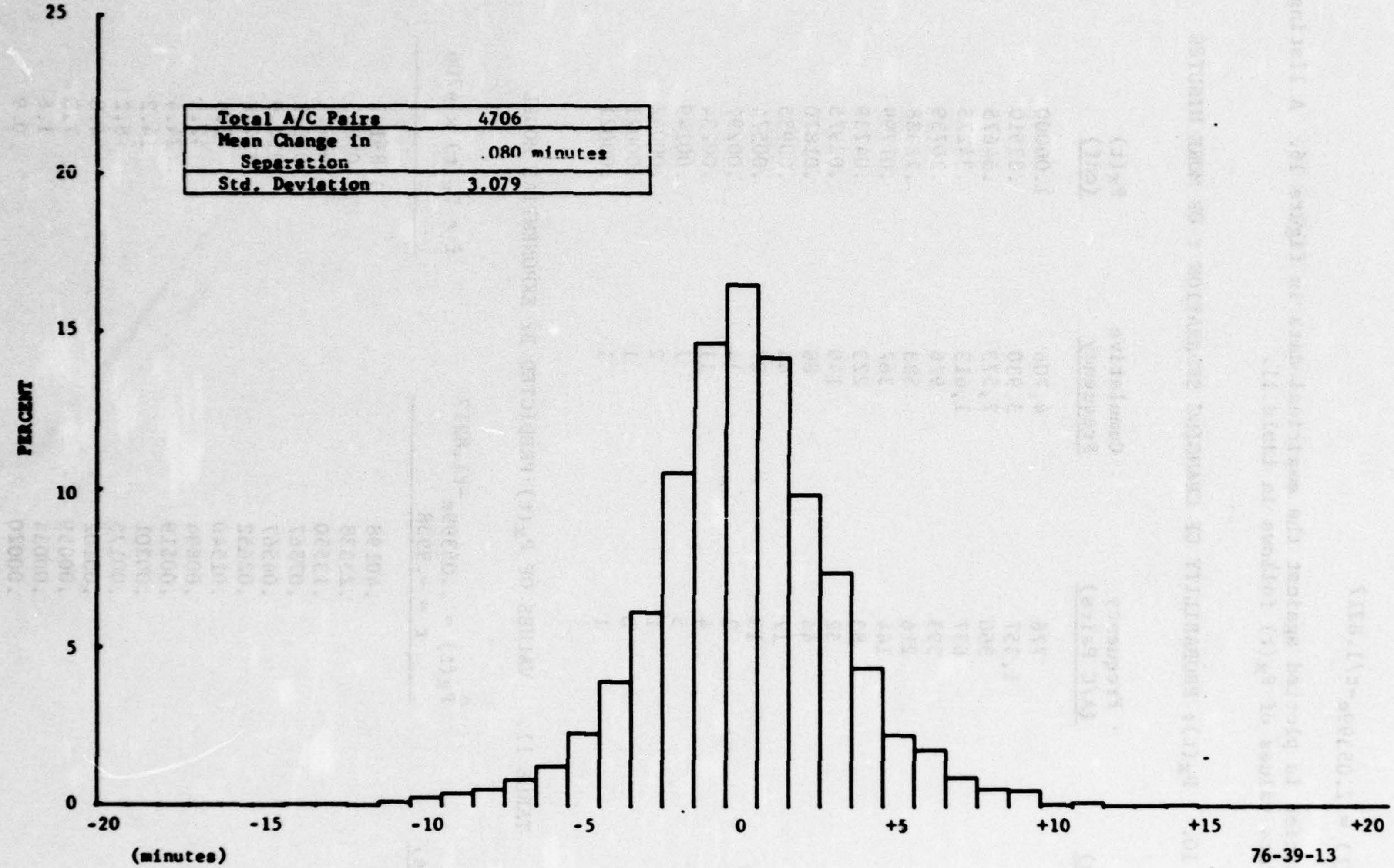


FIGURE 13. RELATIVE FREQUENCY HISTOGRAM OF MACH-ONLY AND NON-MACH CHANGES IN LONGITUDINAL SEPARATION, EAST AND WESTBOUND TRAFFIC

$$\hat{P}_x(t) = 2.05399e^{-t/1.8217}$$

This equation is plotted against the empirical data in figure 16. A listing of discrete values of $P_x(t)$ follows in table 11.

TABLE 10. $P_x(t)$: PROBABILITY OF CHANGING SEPARATION t OR MORE MINUTES

Time, t (Minutes)	Frequency (A/C Pairs)	Cumulative Frequency	$P_x(t)$ (cdf)
0	776	4,706	1.00000
1	1,357	3,930	.83510
2	960	2,573	.54675
3	637	1,613	.34275
4	393	976	.20739
5	216	583	.12388
6	144	367	.07799
7	83	223	.04739
8	52	140	.02975
9	44	88	.01870
10	17	44	.00935
11	13	27	.00574
12	3	14	.00297
13	4	11	.00234
14	5	7	.00149
15	1	2	.00042
16	0	1	.00021
17	1	1	.00021

TABLE 11. VALUES OF $P_x(t)$ PREDICTED BY EXPONENTIAL MODEL

Time, t (Minutes)	$\hat{P}_x(t) = 2.05399e^{-t1.8217}$ $r = -.9958$	$f = \hat{P}_x(t) \times 4706$
3	.40198	1,891.7
4	.23338	1,098.3
5	.13550	637.7
6	.07867	370.2
7	.04567	214.9
8	.02652	124.8
9	.01540	72.4
10	.00894	42.1
11	.00519	24.4
12	.00301	14.2
13	.00175	8.2
14	.00102	4.8
15	.00059	7.8
16	.00034	1.6
17	.00020	0.9

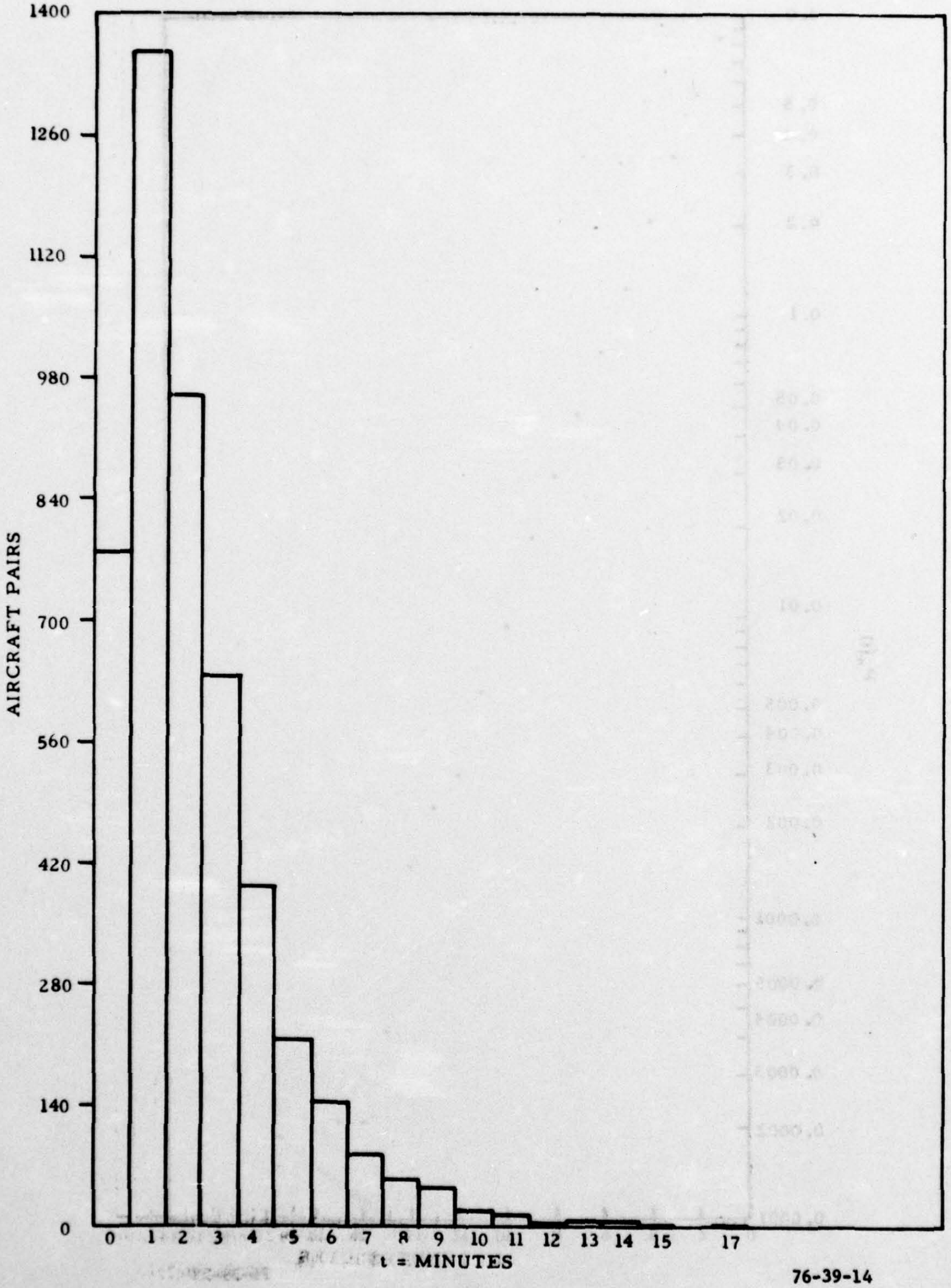


FIGURE 14. FREQUENCY OF CHANGE, T, IN LONGITUDINAL SEPARATION

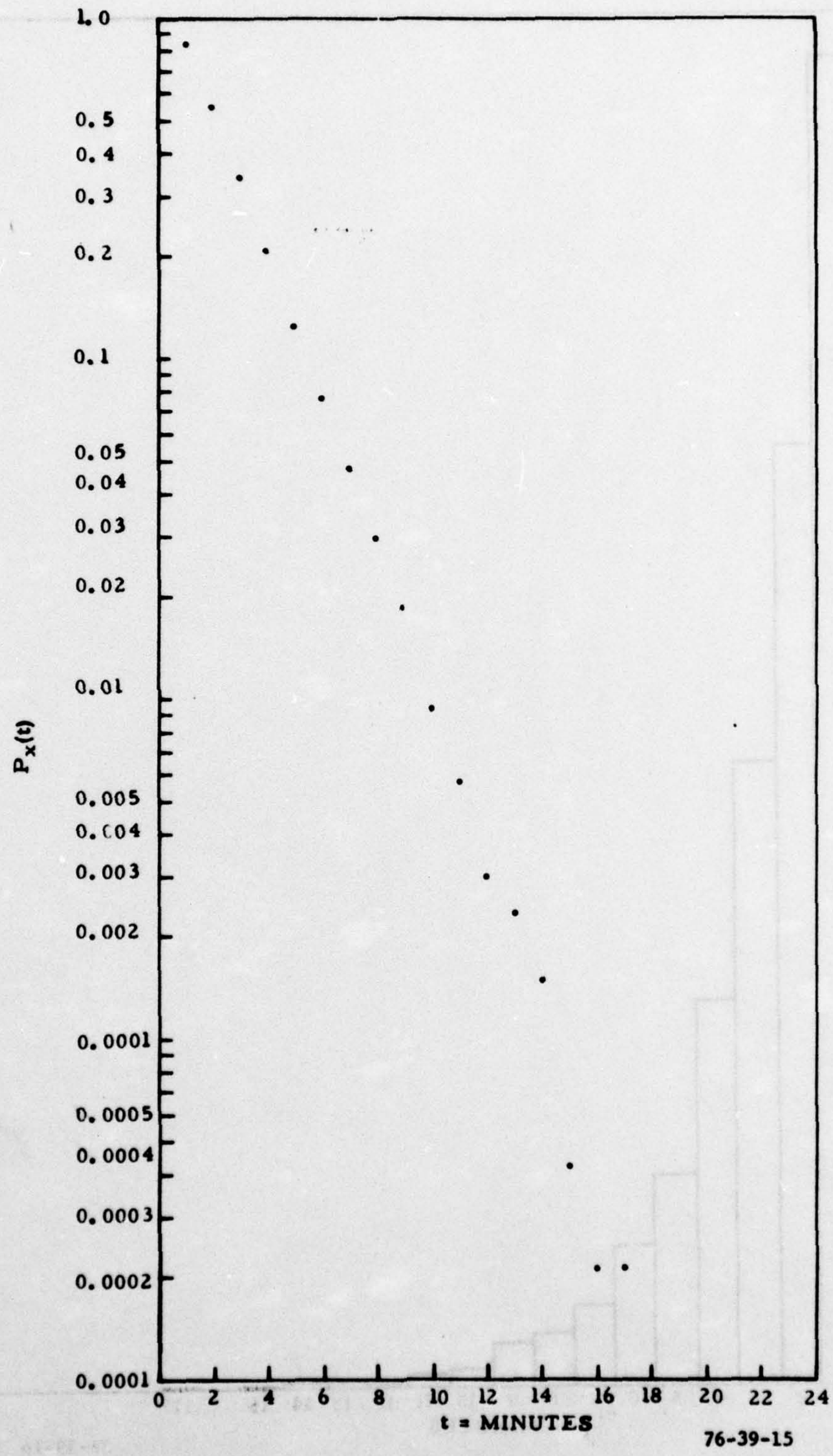


FIGURE 15. PROBABILITY OF OVERTAKE, $P_x(t)$

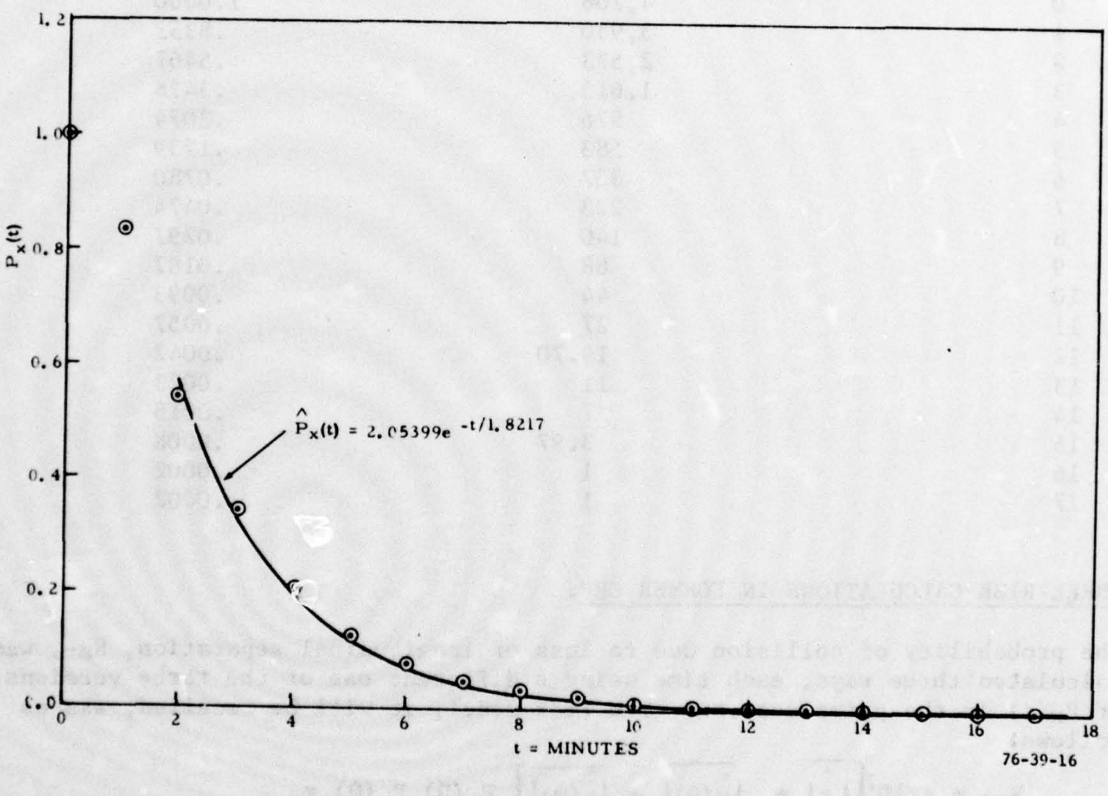


FIGURE 16. LEAST-SQUARES FIT OF EXPONENTIAL FUNCTION TO $P_x(t)$

Also an approach was pursued at the suggestion of consultants from Princeton University. The suggested algorithm (reference 7) was a nonparametric smoother, which assumed only that the distribution of interest has a single peak (unimodal) from which the rest of the data receded. This method resulted in a "unimodalized" version of $P_x(t)$ as presented in table 12.

TABLE 12. $U_x(t)$: UNIMODALIZED VERSION OF $P_x(t)$

Time, t (Minutes)	Frequency (A/C Pairs)	$U_x(t)$
0	4,706	1.0000
1	3,930	.8351
2	2,573	.5467
3	1,613	.3428
4	976	.2074
5	583	.1239
6	367	.0780
7	223	.0474
8	140	.0297
9	88	.0187
10	44	.0093
11	27	.0057
12	19.70	.0042
13	11	.0023
14	7	.0015
15	3.97	.0008
16	1	.0002
17	1	.0002

THREE RISK CALCULATIONS IN FORMER CEP.

The probability of collision due to loss of longitudinal separation, N_{ax}, was calculated three ways, each time using a different one of the three versions of $P_x(t)$ in the prior section. The risk model, it will be recalled, was as follows:

$$N_{ax} = 2\times10^7 \left[\frac{\overline{|\dot{x}|}}{2\lambda_x} + \frac{\overline{|\dot{y}(0)|}}{2\lambda_z} + \frac{\overline{|\dot{z}(0)|}}{2\gamma_z} \right] P_y(0)\, P_z(0)\, \pi_x$$

where $\pi_x = \dfrac{2\lambda x}{|\bar{\dot{x}}|\,(\bar{T})} \Sigma E_x(t)\, P_x(t)$

First, the distribution of $P_x(t)$ based on the empirical data was convolved with $E_x(t)$, yielding the following value for $\Sigma E_x(t)\, P_x(t)$:

t	$E_x(t)$ x	$P_x(t)$ =	$E_x(t)\, P_x(t)$
12	.00012	.00297	.00000036
13	.00006	.00234	.00000014
14	.00036	.00149	.00000054

15	.00164	.00042	.00000070
16	.00316	.00021	.00000067
17	.00431	.00021	.00000092

$$\Sigma E_x(t)\ P_x(t) = .00000333$$
$$\div 2 = 00000232 = 1.62\text{x}10^{-6}$$

Consequently, for the "empirical approach:"

$$N_{ax} = 2\text{x}10^7 \left[\frac{49.33}{2(.033)} + \frac{20}{2(.033)} + \frac{1}{2(.0085)} \right] (.0033) \frac{(.25)(2)(.033)(1.62\text{x}10\text{-}6)}{(49.33)\ (2.42)}$$

or $N_{ax} = .0168$

In a similar manner, a second value of .0189 was calculated using $\hat{P}_x(t)$, the exponential fit, and a third value of .0210 was calculated for $U_x(t)$, the unimodalized version of $P_x(t)$. The risk values for the three approaches are summarized in table 13.

TABLE 13. PROBABILITY OF COLLISION DUE TO LOSS OF LONGITUDINAL SEPARATION

Source of $P_x(t)$	N_{ax} (Accidents per 10^7 Flying Hours)
Empirical Approach	.0168
Exponential Fit	.0189
Unimodal	.0210

SIMULATED RISK CALCULATION IN THE CURRENT COMPOSITE CEP.

On May 20, 1976, a trial composite separation was initiated in the CEP system. Changes were introduced such that six routes crossed the CEP where four had previously handled all the traffic. Alternating routes were raised 1,000 feet, causing aircraft flying parallel in the same direction on adjacent routes to be separated not only by approximately 50 nmi but also by 1,000 feet vertically.

Calculating collision risk for the six-route system differed from that for the four-route system only in the choice of an appropriate distribution to represent initial longitudinal separation between aircraft pairs, $E_x(t)$. It was assumed that longitudinal separation changes, $P_x(t)$, would mimic those for the four-route system, since the changes in lateral and vertical spacing had no direct bearing on an aircraft's along-track maneuvering. The remaining parameters, as listed in table 8, were also assumed to be unaffected by the change in configuration and their values from the four-track system analysis were retained.

Since no data were presently available from which a new $E_x(t)$ could be drawn describing entrance separations in the current six-route system, Esim(t) was generated in a fast-time simulation program using the previously mentioned FHF as input. From this file, a demand function was derived which specified the time that 17,712 aircraft required entry into the system. As in earlier

calculations, the CEP system was defined as the track structure between 130W and 150W longitude. Consequently, demanded entry times were either the reported 130W crossing time for eastbound flights or the 150W time for westbound.

Whenever, in the simulation, an aircraft arrived seeking ingress to the system, the program assigned it a route and altitude based on two criteria, (1) optimal routing (most fuel-efficient for that aircraft type), and (2) availability of that optimal routing. If an aircraft's most preferred routing was not available, a second-, third-, fourth-, or fifth-ranked alternative was assigned depending on its availability. No aircraft was ever assigned a particular route and altitude if it could be expected, through a change in separation, to violate the 15-minute minimum separation before it completed its flight.

A summary of a typical "effective" initial separation distribution, $E_{sim}(t)$, thus generated, is presented in table 14. A K-S test confirmed that the difference between $E_{sim}(t)$ and the empirically derived $E_x(t)$ was not statistically significant.

TABLE 14. $E_{sim}(t)$: COMPUTER SIMULATION OF $E_x(t)$ FOR FOUR-ROUTE CEP (N=17,712)

Initial Separation (Minutes)	Frequency (A/C Pairs)	$E_{sim}(t)$
13	3	.00017
14	11	.00062
15	16	.00090
16	46	.00260
17	77	.00435
18	120	.00678
19	122	.00689
20	157	.00886
21	153	.00864
22	180	.01016
23	161	.00909
24	196	.01107
25	161	.00909
26	160	.00903
27	171	.00965
28	188	.01061
29	160	.00903
30	161	.00909

Further validation of the simulation technique was gained in the risk calculation itself. Employing $E_{sim}(t)$, a risk value, N_{ax}, of .0160 accidents per 10 million flying hours was computed for the four-route system. This result compared favorably with the .0168 empirical value, differing by only 4.76 percent. Hence, the methodology was extended to the six-route system (table 15) yielding a risk value of .0130, lower than the four-route system by 18.75 percent (table 16).

TABLE 15. $E_{sim}(t)$: COMPUTER SIMULATION OF $E_x(t)$ FOR COMPOSITE SIX-ROUTE CEP (N=17,712)

Initial Separation (Minutes)	Frequency (A/C Pairs)	$E_{sim}(t)$
11	1	.00006
12	0	.00000
13	2	.00011
14	4	.00023
15	23	.00130
16	33	.00186
17	60	.00339
18	81	.00457
19	109	.00615
20	127	.00717
21	120	.00678
22	137	.00773
23	160	.00903
24	132	.00745
25	131	.00740
26	123	.00694
27	144	.00813
28	145	.00819
29	133	.00751
30	131	.00740

TABLE 16. SIMULATED N_{ax} (ACCIDENTS PER 10^7 FLYING HOURS)

	N_{ax}
Four-Route Simulation	.0160
Six-Route Simulation	.0130

RISK AND AIRCRAFT WITH INS.

In order to determine the relative influences on collision risk of employing different levels of equipment sophistication, the three navigation groupings were each used as a source of $P_x(t)$ in the risk calculation. Numerical values of the respective distributions are presented in table 17. It is assumed that the same effective initial separations will hold ($E_x(t)$), but that the changes in separation will be those characteristic of (1) all aircraft flying INS (INS-INS), (2) every second aircraft flying INS (INS-Other), and (3) no aircraft flying INS (Other-Other). Since the probability of lateral overlap for same-route, coaltitude aircraft, $P_y(0)$, is a direct function of navigation equipment,

a value for $P_y(0)$ consistent with INS-equipped aircraft's improved track-keeping ability was calculated from radar data to be .0042. Using the original value (.0033) for Other-Other and midpoint value for INS-Other (.00375), the results in table 18 were obtained for N_{ax}. As can be seen, risk decreases as the proportion of INS-type aircraft with better air data systems increase.

TABLE 17. $P_x(t)$ AS A FUNCTION OF NAVIGATION EQUIPMENT

Time, t (Minutes)	$P_x(t)$ INS-INS n = 1,456	$P_x(t)$ INS-OTHER n = 2,109	$P_x(t)$ OTHER-OTHER n = 1,141
0	1.0000	1.0000	1.0000
1	.7919	.8468	.8685
2	.4478	.5775	.6161
3	.2555	.3589	.4242
4	.1490	.2105	.2761
5	.0797	.1309	.1674
6	.0440	.0877	.1034
7	.0288	.0503	.0657
8	.0158	.0303	.0465
9	.0096	.0190	.0298
10	.0041	.0085	.0175
11	.0014	.0062	.0105
12	.0007	.0028	.0061
13	-	.0024	.0053
14	-	.0019	.0026
15	-	.0005	.0009
16	-	-	.0009
17	-	-	.0009

TABLE 18. N_{ax} (ACCIDENTS PER 10^7 FLYING HOURS) AS A FUNCTION OF NAVIGATION EQUIPMENT

INS-INS	.00042
INS-Other	.00988
Other-Other	.05053

SENSITIVITY ANALYSIS.

The current, statutory, along-track separation minimum, L_x, is 15 minutes. An analysis was performed to gauge the effect on risk of varying L_x from 20 to 10 minutes in 1-minute decrements.

As was noted earlier, aircraft arrived at the entrance points to the track system with effective initial separations, t, as described by $E_x(t)$ (table 9). The assumption was made that aircraft would disperse themselves in the same manner relative to L_x such that $E_x(t)$ for the four-route CEP system could also be represented as it is in table 19.

TABLE 19. $E_x(t)$ AS A FUNCTION OF L_x (FOUR-ROUTE CEP)

Time, t	$E_x(t)$
L_x-3	.00012
L_x-2	.00006
L_x-1	.00036
L_x	.00164
L_x+1	.00316
L_x+2	.00431
L_x+3	.00546
L_x+4	.00613
L_x+5	.00819
L_x+6	.00722
L_x+7	.00837
L_x+8	.00898
L_x+9	.00801
L_x+10	.00789

This "standardized" version of $E_x(t)$ was used with $P_x(t)$, the probability of overtake, in the risk calculations across the range of values of L_x. Two separate distributions were used for $P_x(t)$: (1) $P_x(t)$, the empirical distribution for all aircraft, table 10, and (2) $P_x(t)$ for INS-equipped aircraft only, table 17. Contrasting the risk results for these two groups is akin to comparing risk in the CEP system with risk in an all-INS-type aircraft CEP system. The results follow in table 20.

As is evident in table 20, an INS-only system with the current minimum along-track separation, L_x, of 15 minutes should be considerably safer in terms of longitudinal risk than the four-route system with L_x also equaling 15. Or, if all flights were to maintain separation as well as the INS-equipped aircraft in this sample, L_x could possibly be reduced without any substantive increase to the current longitudinal collision risk.

In order to gauge the effect of varying L_x in the six-route CEP, a similar exercise was performed using $E_{sim}(t)$ for the six-route system, as listed in table 15. Standardizing this distribution to L_x yielded the $E_x(t)$ of table 21.

TABLE 20. COMPARISON OF LONGITUDINAL COLLISION RISK FOR VARIOUS VALUES OF L_x IN THE FOUR-ROUTE CEP

L_x (Minutes)	N_{ax} All A/C $P_y(0) = .0033$	N_{ax} INS-Only $P_y(0) = .0042$
8	>.4	>.4
9	>.4	.3298
10	>.4	.1415
11	.2578	.0541
12	.1463	.0196
13	.0777	.0053
14	.0383	.0014
15	.0168	.0005
16	.0078	
17	.0032	
18	.0007	
19	.0002	
20	.0001	

TABLE 21. $E_x(t)$ AS A FUNCTION OF L_x (SIX-ROUTE CEP)

Time, t	$E_x(t)$
L_x-4	.00006
L_x-3	.00000
L_x-2	.00011
L_x-1	.00023
L_x	.00130
L_x+1	.00186
L_x+2	.00339
L_x+3	.00457
L_x+4	.00615
L_x+5	.00717
L_x+6	.00678
L_x+7	.00773
L_x+8	.00903
L_x+9	.00745
L_x+10	.00740

As before, two versions of $P_x(t)$ were employed in risk calculations, such that a comparison of INS-equipped aircraft only versus all aircraft could be made of the risk in the six-route track structure. The results in table 22 lend themselves tc conclusions similar to the four-route case.

TABLE 22. COMPARISON OF LONGITUDINAL RISK FOR VARIOUS VALUES OF L_x IN THE SIX-ROUTE CEP

L_x (Minutes)	N_{ax} All A/C $P_y(0) = .0033$	N_{ax} INS-Equipped $P_y(0) = .0042$
8	>.4	>.4
9	>.4	.2526
10	.3849	.1072
11	.2183	.0431
12	.1198	.0165
13	.0646	.0055
14	.0344	.0020
15	.0141	.0005
16	.0060	.0003
17	.0027	
18	.0008	
19	.0003	
20	.0001	

For instance, a projected system with all aircraft performing as the INS-equipped in this sample consistently produced a lower collision risk value despite the sample's higher probability of lateral overlap, $P_y(0)$. Consequently, L_x could be reduced significantly before an acceptable level of safety would be exceeded. However, all flights would have to maintain separation as INS-equipped flights in this sample, before L_x could potentially be reduced. Also, before the reader advocates any reduction of longitudinal separation, two more cautions should be observed. First, since the shifting of the data presented in figure 12 is probably not realistic of what proportion of the air traffic could or would take advantage of a reduction of L_x, but instead assumes that the system is very crowded, the projected shrinkage of L_x is a conservative upper bound estimate. Secondly, any final recommendation for reducing L_x must consider its impact on lateral collision risk and the effect of future increases in traffic density.

SUMMARY

An analysis of longitudinal separation of aircraft traversing the CEP was performed using data collected on 18,164 flights in the CEP in the first 6 months of 1974. Interarrival times on entrance to and exit from the CEP route system were generated, as were changes in initial versus final along-track separations for all those aircraft pairs entering the CEP within 60 minutes of one another at the same entrance points (route and altitude) of the system. These changes in longitudinal separation enroute were grouped according to (1) the mach number differences between the pair members and (2) the absence or presence of INS aboard the two aircraft. A worst-case nomograph was produced for predicting maximum expected changes in longitudinal separation of aircraft flying mach number spacing on long distance flights across the ocean. Finally, various values of collision risk due to loss of longitudinal separation were calculated using a revised NAT/SPG methodology and estimating parameters, where necessary, based on the data.

CONCLUSIONS

From the results, it is concluded that:

1. Mach number spacing techniques as used in the CEP track system are effective methods for maintenance of safe longitudinal separation using current separation criteria and enroute monitoring and adjustment procedures.

2. A significant improvement (P>.99) in the ability to maintain longitudinal separation can be attributed to those aircraft employing mach number spacing techniques when contrasted with those not using the techniques in the CEP track system.

3. Those aircraft types identified as having INS navigation systems perform significantly better (P>.99) in maintaining longitudinal separation enroute than non-INS-equipped aircraft. The cause of this phenomenon has not been fully ascertained.

4. In the old four-route CEP system and in the current six-route CEP composite system, risk of collision due to the loss of longitudinal separation as calculated by the revised method presented in this report is less than the Target Level of Safety used by the NAT/SPG.

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APPENDIX A

ENTRANCE AND EXIT SEPARATIONS BY ROUTE AND ALTITUDE

TABLE A-1. FREQUENCY OF GIVEN TIME SEPARATION AT ENTRANCE GATEWAY

MINUTES

N.BOUND :	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE .	F.L. = 280
14	0.	0.	0.	0.	
15	0.	0.	0.	0.	
16	0.	0.	0.	0.	
17	0.	1.	0.	0.	
18	0.	0.	0.	0.	
19	0.	0.	0.	0.	
20	0.	0.	0.	0.	
21	0.	0.	0.	0.	
22	0.	0.	0.	0.	
23	0.	0.	0.	0.	
24	0.	0.	0.	0.	
25	0.	0.	0.	0.	
26	0.	1.	0.	0.	
27	0.	0.	0.	0.	
28	0.	0.	0.	0.	
29	0.	0.	0.	0.	
30	0.	2.	0.	0.	
31	0.	0.	0.	0.	
32	0.	0.	0.	0.	
33	0.	0.	0.	0.	
34	0.	0.	0.	0.	
35	0.	0.	0.	0.	
36	0.	0.	0.	0.	
37	0.	0.	0.	0.	
38	0.	0.	0.	0.	
39	0.	0.	0.	0.	
40	0.	1.	0.	0.	
41	0.	0.	0.	0.	
42	0.	0.	0.	0.	
43	0.	0.	0.	0.	
44	0.	0.	0.	0.	
45	0.	0.	0.	0.	
46	0.	0.	0.	0.	
47	0.	0.	0.	0.	
48	0.	0.	0.	0.	
49	0.	0.	0.	0.	
50	0.	0.	0.	0.	
51	0.	0.	0.	0.	
52	0.	0.	0.	0.	
53	0.	0.	0.	0.	
54	0.	0.	0.	0.	
55	0.	0.	0.	0.	
56	0.	0.	0.	0.	
57	0.	0.	0.	0.	
58	0.	0.	1.	0.	
59	0.	0.	0.	0.	
60	0.	0.	0.	0.	

76-39-A-1

TABLE A-2. FREQUENCY OF GIVEN TIME SEPARATION AT ENTRANCE GATEWAY

MINUTES

E.BCLNC I	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE	F.L. = 290
14	0.	0.	0.	0.	
15	0.	0.	0.	0.	
16	0.	0.	0.	0.	
17	0.	0.	0.	0.	
18	0.	0.	0.	0.	
19	0.	0.	0.	0.	
20	0.	0.	0.	0.	
21	0.	0.	0.	0.	
22	0.	0.	1.	0.	
23	0.	0.	0.	0.	
24	0.	0.	0.	0.	
25	0.	0.	0.	0.	
26	0.	0.	0.	0.	
27	0.	0.	0.	0.	
28	0.	0.	0.	0.	
29	0.	1.	0.	0.	
30	0.	0.	0.	0.	
31	0.	0.	0.	0.	
32	0.	0.	0.	0.	
33	0.	0.	0.	0.	
34	0.	0.	0.	0.	
35	0.	0.	0.	0.	
36	0.	0.	1.	0.	
37	0.	0.	0.	0.	
38	0.	1.	0.	0.	
39	0.	0.	0.	0.	
40	0.	0.	0.	0.	
41	0.	0.	0.	0.	
42	0.	0.	0.	0.	
43	0.	0.	0.	0.	
44	0.	0.	0.	0.	
45	0.	0.	1.	0.	
46	0.	0.	0.	0.	
47	0.	1.	0.	0.	
48	0.	0.	0.	0.	
49	0.	0.	0.	0.	
50	0.	2.	0.	0.	
51	0.	0.	0.	0.	
52	0.	0.	0.	0.	
53	0.	1.	0.	0.	
54	0.	0.	0.	0.	
55	0.	0.	0.	0.	
56	0.	0.	0.	0.	
57	0.	0.	0.	0.	
58	0.	1.	1.	0.	
59	0.	0.	0.	0.	
60	0.	1.	0.	0.	

76-39-A-2

TABLE A-3. FREQUENCY OF GIVEN TIME SEPARATION AT ENTRANCE GATEWAY

W.BOUND :	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE	F.L. = 310
14	0.	0.	0.	0.	
15	0.	0.	0.	0.	
16	0.	2.	1.	0.	
17	0.	3.	2.	0.	
18	0.	1.	4.	0.	
19	0.	4.	5.	0.	
20	0.	4.	4.	0.	
21	0.	6.	4.	0.	
22	0.	3.	7.	0.	
23	0.	8.	7.	0.	
24	0.	8.	2.	0.	
25	0.	4.	10.	1.	
26	0.	8.	7.	1.	
27	0.	4.	6.	0.	
28	0.	1.	4.	0.	
29	0.	8.	12.	0.	
30	0.	6.	8.	0.	
31	0.	2.	3.	1.	
32	0.	4.	7.	0.	
33	0.	5.	2.	0.	
34	0.	6.	6.	0.	
35	0.	5.	7.	0.	
36	0.	5.	3.	0.	
37	0.	2.	5.	0.	
38	0.	4.	2.	0.	
39	0.	3.	8.	1.	
40	0.	6.	5.	0.	
41	0.	5.	5.	0.	
42	0.	3.	8.	0.	
43	0.	5.	3.	1.	
44	1.	4.	6.	0.	
45	0.	5.	8.	1.	
46	0.	4.	6.	2.	
47	0.	6.	7.	0.	
48	0.	9.	3.	1.	
49	0.	8.	3.	0.	
50	0.	4.	4.	0.	
51	0.	4.	2.	0.	
52	0.	4.	5.	0.	
53	0.	5.	4.	1.	
54	0.	3.	6.	0.	
55	0.	8.	6.	0.	
56	0.	4.	5.	0.	
57	0.	6.	4.	0.	
58	0.	5.	2.	0.	
59	0.	1.	4.	0.	
60	0.	3.	4.	0.	

MINUTES

76-39-A-3

TABLE A-4. FREQUENCY OF GIVEN TIME SEPARATION AT ENTRANCE GATEWAY

MINUTES

E.BOUND :	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE	F.L. = 330
14	0.	0.	0.	0.	
15	0.	0.	5.	0.	
16	0.	3.	5.	0.	
17	0.	5.	7.	0.	
18	0.	3.	5.	0.	
19	1.	4.	6.	0.	
20	0.	3.	5.	1.	
21	0.	3.	8.	0.	
22	1.	12.	12.	0.	
23	0.	5.	8.	0.	
24	0.	9.	8.	0.	
25	0.	6.	5.	0.	
26	0.	6.	12.	0.	
27	0.	8.	8.	0.	
28	0.	5.	5.	0.	
29	0.	4.	6.	0.	
30	0.	8.	6.	0.	
31	0.	7.	6.	0.	
32	0.	11.	10.	0.	
33	0.	13.	6.	0.	
34	1.	10.	2.	0.	
35	1.	11.	9.	0.	
36	0.	13.	7.	0.	
37	0.	9.	8.	0.	
38	0.	7.	5.	0.	
39	0.	6.	5.	0.	
40	0.	3.	2.	0.	
41	0.	7.	11.	0.	
42	0.	3.	8.	0.	
43	0.	8.	7.	1.	
44	0.	10.	7.	0.	
45	0.	4.	6.	0.	
46	0.	5.	3.	0.	
47	0.	4.	3.	0.	
48	0.	5.	6.	1.	
49	0.	6.	8.	0.	
50	0.	1.	10.	0.	
51	0.	8.	4.	1.	
52	0.	4.	2.	0.	
53	0.	1.	5.	0.	
54	1.	4.	10.	0.	
55	0.	11.	2.	0.	
56	0.	6.	5.	0.	
57	0.	2.	5.	0.	
58	1.	4.	5.	1.	
59	0.	9.	6.	0.	
60	0.	9.	0.	1.	

76-39-A-4

TABLE A-5. FREQUENCY OF GIVEN TIME SEPARATION AT ENTRANCE GATEWAY

F.L. = 350

MINUTES

W.BOUND :	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE
14	0.	0.	0.	0.
15	1.	4.	4.	1.
16	1.	12.	13.	1.
17	0.	8.	18.	1.
18	1.	13.	26.	1.
19	0.	12.	33.	2.
20	2.	19.	28.	1.
21	3.	19.	30.	0.
22	1.	18.	34.	2.
23	1.	30.	20.	2.
24	0.	20.	22.	2.
25	2.	23.	35.	3.
26	3.	22.	17.	3.
27	1.	22.	24.	2.
28	2.	21.	33.	0.
29	2.	17.	31.	3.
30	3.	16.	25.	3.
31	2.	25.	23.	1.
32	0.	22.	17.	5.
33	1.	20.	21.	0.
34	0.	24.	19.	4.
35	1.	16.	20.	3.
36	1.	15.	32.	3.
37	2.	24.	24.	2.
38	1.	23.	15.	4.
39	1.	20.	13.	4.
40	0.	18.	15.	1.
41	2.	18.	12.	4.
42	2.	26.	8.	8.
43	1.	16.	12.	3.
44	0.	17.	28.	3.
45	0.	17.	19.	7.
46	1.	13.	24.	5.
47	1.	14.	12.	5.
48	1.	17.	22.	4.
49	4.	9.	14.	3.
50	1.	21.	19.	6.
51	1.	18.	16.	2.
52	1.	13.	11.	2.
53	1.	15.	15.	1.
54	1.	14.	13.	2.
55	2.	13.	9.	3.
56	2.	17.	14.	3.
57	0.	9.	11.	2.
58	1.	10.	16.	2.
59	1.	18.	14.	2.
60	1.	16.	14.	1.

76-39-A-5

TABLE A-6. FREQUENCY OF GIVEN TIME SEPARATION AT ENTRANCE GATEWAY

E.BOUND : (MINUTES)	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE
14	0.	1.	1.	0.
15	0.	2.	4.	0.
16	1.	9.	19.	0.
17	0.	4.	19.	0.
18	0.	9.	31.	0.
19	0.	15.	36.	1.
20	1.	16.	45.	1.
21	0.	20.	37.	0.
22	1.	24.	31.	0.
23	1.	13.	39.	2.
24	1.	17.	38.	1.
25	0.	22.	35.	2.
26	0.	19.	39.	1.
27	2.	21.	33.	0.
28	0.	15.	33.	1.
29	0.	15.	27.	0.
30	0.	13.	33.	2.
31	0.	14.	28.	2.
32	1.	24.	22.	0.
33	0.	10.	17.	1.
34	0.	17.	30.	0.
35	1.	15.	22.	6.
36	1.	24.	13.	0.
37	0.	18.	23.	0.
38	0.	10.	28.	2.
39	0.	18.	20.	0.
40	0.	27.	23.	2.
41	1.	19.	17.	0.
42	0.	17.	24.	1.
43	0.	12.	13.	3.
44	0.	15.	20.	1.
45	0.	17.	15.	2.
46	2.	12.	22.	3.
47	0.	18.	11.	1.
48	0.	12.	14.	2.
49	1.	10.	21.	1.
50	1.	9.	13.	0.
51	0.	17.	16.	2.
52	0.	10.	10.	1.
53	0.	9.	20.	1.
54	0.	10.	11.	1.
55	0.	17.	15.	1.
56	0.	14.	17.	1.
57	0.	10.	17.	1.
58	1.	12.	13.	4.
59	0.	20.	10.	0.
60	0.	26.	12.	0.

F.L. = 370

76-39-A-6

TABLE A-7. FREQUENCY OF GIVEN TIME SEPARATION AT ENTRANCE GATEWAY

N.BOUND :	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE	F.L. = 390
14	0.	1.	1.	0.	
15	0.	0.	0.	0.	
16	0.	4.	1.	0.	
17	0.	1.	1.	0.	
18	0.	1.	0.	0.	
19	0.	5.	0.	0.	
20	1.	2.	0.	0.	
21	0.	8.	0.	0.	
22	0.	5.	2.	0.	
23	0.	2.	0.	0.	
24	0.	2.	1.	0.	
25	0.	6.	2.	0.	
26	0.	3.	2.	0.	
27	0.	5.	2.	0.	
28	0.	1.	0.	0.	
29	0.	3.	1.	0.	
30	0.	5.	0.	0.	
31	0.	6.	0.	0.	
32	0.	5.	1.	0.	
33	1.	2.	0.	0.	
34	0.	6.	1.	0.	
35	0.	4.	0.	1.	
36	0.	3.	0.	0.	
37	0.	4.	2.	0.	
38	0.	2.	1.	0.	
39	0.	7.	1.	0.	
40	0.	1.	1.	0.	
41	0.	3.	0.	0.	
42	0.	3.	0.	0.	
43	0.	4.	0.	0.	
44	0.	5.	1.	0.	
45	0.	2.	0.	0.	
46	0.	2.	0.	0.	
47	0.	4.	0.	0.	
48	0.	2.	1.	0.	
49	0.	3.	1.	0.	
50	0.	2.	0.	0.	
51	0.	2.	1.	0.	
52	0.	2.	0.	0.	
53	0.	5.	0.	0.	
54	1.	4.	0.	0.	
55	0.	6.	1.	0.	
56	0.	4.	0.	0.	
57	0.	3.	0.	0.	
58	0.	3.	0.	0.	
59	0.	3.	0.	0.	
60	0.	5.	0.	0.	

MINUTES

76-39-A-7

TABLE A-8. FREQUENCY OF GIVEN TIME SEPARATION AT ENTRANCE GATEWAY

	E.BELNC :	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE	F.L. = 41C
MINUTES	14	0.	0.	0.	0.	
	15	0.	0.	0.	0.	
	16	0.	0.	0.	0.	
	17	0.	0.	0.	0.	
	18	0.	0.	0.	0.	
	19	0.	1.	0.	0.	
	20	0.	0.	0.	0.	
	21	0.	0.	0.	0.	
	22	0.	0.	0.	0.	
	23	0.	0.	0.	0.	
	24	0.	0.	0.	0.	
	25	0.	0.	0.	0.	
	26	0.	0.	0.	0.	
	27	0.	0.	0.	0.	
	28	0.	0.	0.	0.	
	29	0.	0.	0.	0.	
	30	0.	0.	0.	0.	
	31	0.	0.	0.	0.	
	32	0.	0.	0.	0.	
	33	0.	0.	0.	0.	
	34	0.	0.	0.	0.	
	35	0.	0.	0.	0.	
	36	0.	0.	0.	0.	
	37	0.	1.	0.	0.	
	38	0.	0.	0.	0.	
	39	0.	0.	0.	0.	
	40	0.	1.	0.	0.	
	41	0.	0.	0.	0.	
	42	0.	0.	0.	0.	
	43	0.	0.	0.	0.	
	44	0.	0.	0.	0.	
	45	0.	0.	0.	0.	
	46	0.	0.	0.	0.	
	47	0.	0.	0.	0.	
	48	0.	0.	0.	0.	
	49	0.	0.	0.	0.	
	50	0.	0.	0.	0.	
	51	0.	0.	0.	0.	
	52	0.	0.	0.	0.	
	53	0.	0.	0.	0.	
	54	0.	0.	0.	0.	
	55	0.	0.	0.	0.	
	56	0.	0.	0.	0.	
	57	0.	0.	1.	0.	
	58	0.	0.	0.	0.	
	59	0.	0.	0.	0.	
	60	0.	0.	0.	0.	

76-39-A-8

TABLE A-9. FREQUENCY OF GIVEN TIME SEPARATION AT ENTRANCE GATEWAY

N.BOUND : MINUTES	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE	F.L. = 430
14	0.	0.	0.	0.	
15	0.	0.	0.	0.	
16	0.	0.	0.	0.	
17	0.	0.	0.	0.	
18	0.	0.	0.	0.	
19	0.	0.	0.	0.	
20	0.	0.	0.	0.	
21	0.	0.	0.	0.	
22	0.	0.	0.	0.	
23	0.	0.	0.	0.	
24	0.	0.	0.	0.	
25	0.	0.	0.	0.	
26	0.	0.	0.	0.	
27	0.	0.	0.	0.	
28	0.	0.	0.	0.	
29	0.	0.	0.	0.	
30	0.	0.	0.	0.	
31	0.	0.	0.	0.	
32	0.	0.	0.	0.	
33	0.	0.	0.	0.	
34	0.	0.	0.	0.	
35	0.	0.	0.	0.	
36	0.	0.	0.	0.	
37	0.	0.	0.	0.	
38	0.	0.	0.	0.	
39	0.	0.	0.	0.	
40	0.	0.	0.	0.	
41	0.	0.	0.	0.	
42	0.	0.	0.	0.	
43	0.	0.	0.	0.	
44	0.	0.	0.	0.	
45	0.	0.	0.	0.	
46	0.	0.	0.	0.	
47	0.	0.	0.	0.	
48	0.	0.	0.	0.	
49	0.	0.	0.	0.	
50	0.	0.	0.	0.	
51	0.	0.	0.	0.	
52	0.	0.	0.	0.	
53	0.	0.	0.	0.	
54	0.	0.	0.	0.	
55	0.	0.	0.	0.	
56	0.	0.	0.	0.	
57	0.	1.	0.	0.	
58	0.	0.	0.	0.	
59	0.	0.	0.	0.	
60	0.	1.	0.	0.	

76-39-A-9

TABLE A-10. FREQUENCY OF GIVEN TIME SEPARATION AT EXIT GATEWAY

N.DELAY : MINUTES	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE	F.L. = 280
9	0.	0.	0.	0.	
10	0.	0.	0.	0.	
11	0.	0.	0.	0.	
12	0.	0.	0.	0.	
13	0.	0.	0.	0.	
14	0.	0.	0.	0.	
15	0.	0.	0.	0.	
16	0.	0.	0.	0.	
17	0.	0.	0.	0.	
18	0.	0.	0.	0.	
19	0.	0.	0.	0.	
20	0.	0.	0.	0.	
21	0.	0.	0.	0.	
22	0.	0.	0.	0.	
23	0.	0.	0.	0.	
24	0.	1.	0.	0.	
25	0.	0.	0.	0.	
26	0.	0.	0.	0.	
27	0.	0.	0.	0.	
28	0.	0.	0.	0.	
29	0.	0.	0.	0.	
30	0.	1.	0.	0.	
31	0.	1.	0.	0.	
32	0.	0.	0.	0.	
33	0.	0.	0.	0.	
34	0.	0.	0.	0.	
35	0.	0.	0.	0.	
36	0.	0.	0.	0.	
37	0.	1.	0.	0.	
38	0.	0.	0.	0.	
39	0.	0.	0.	0.	
40	0.	0.	0.	0.	
41	0.	0.	0.	0.	
42	0.	1.	0.	0.	
43	0.	0.	0.	0.	
44	0.	0.	0.	0.	
45	0.	0.	0.	0.	
46	0.	0.	0.	0.	
47	0.	0.	0.	0.	
48	0.	0.	0.	0.	
49	0.	0.	0.	0.	
50	0.	0.	0.	0.	
51	0.	0.	0.	0.	
52	0.	0.	0.	0.	
53	0.	0.	0.	0.	
54	0.	0.	0.	0.	
55	0.	0.	0.	0.	
56	0.	0.	0.	0.	
57	0.	0.	0.	0.	
58	0.	0.	0.	0.	
59	0.	0.	0.	0.	
60	0.	0.	0.	0.	

76-39-A-10

TABLE A-11. FREQUENCY OF GIVEN TIME SEPARATION AT EXIT GATEWAY

MINUTES

E.BOUND :	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE	F.L. = 290
9	0.	0.	0.	0.	
10	0.	0.	0.	0.	
11	0.	0.	0.	0.	
12	0.	0.	0.	0.	
13	0.	0.	0.	0.	
14	0.	0.	0.	0.	
15	0.	0.	0.	0.	
16	0.	0.	0.	0.	
17	0.	0.	0.	0.	
18	0.	1.	0.	0.	
19	0.	0.	0.	0.	
20	0.	0.	0.	0.	
21	0.	0.	0.	0.	
22	0.	0.	0.	0.	
23	0.	0.	0.	0.	
24	0.	0.	0.	0.	
25	0.	0.	1.	0.	
26	0.	0.	0.	0.	
27	0.	0.	0.	0.	
28	0.	0.	0.	0.	
29	0.	0.	0.	0.	
30	0.	0.	1.	0.	
31	0.	0.	0.	0.	
32	0.	0.	0.	0.	
33	0.	0.	0.	0.	
34	0.	0.	0.	0.	
35	0.	0.	0.	0.	
36	0.	0.	0.	0.	
37	0.	0.	0.	0.	
38	0.	0.	0.	0.	
39	0.	0.	0.	0.	
40	0.	0.	0.	0.	
41	0.	1.	0.	0.	
42	0.	1.	1.	0.	
43	0.	0.	0.	0.	
44	0.	0.	0.	0.	
45	0.	0.	0.	0.	
46	0.	0.	0.	0.	
47	0.	0.	1.	0.	
48	0.	0.	0.	0.	
49	0.	0.	0.	0.	
50	0.	0.	0.	0.	
51	0.	1.	0.	0.	
52	0.	0.	0.	0.	
53	0.	1.	0.	0.	
54	0.	0.	0.	0.	
55	0.	0.	0.	0.	
56	0.	0.	0.	0.	
57	0.	1.	0.	0.	
58	0.	1.	0.	0.	
59	0.	0.	0.	0.	
60	0.	0.	0.	0.	

76-39-A-11

TABLE A-12. FREQUENCY OF GIVEN TIME SEPARATION AT EXIT GATEWAY

N.BOUND :	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE	F.L. = 310
9	0.	0.	0.	0.	
10	0.	0.	0.	0.	
11	0.	0.	0.	0.	
12	0.	0.	0.	0.	
13	0.	0.	0.	0.	
14	0.	0.	1.	0.	
15	0.	2.	1.	0.	
16	0.	0.	2.	0.	
17	0.	3.	3.	0.	
18	0.	2.	2.	0.	
19	0.	1.	4.	0.	
20	0.	5.	3.	0.	
21	0.	6.	2.	0.	
22	0.	5.	6.	0.	
23	0.	3.	6.	0.	
24	0.	6.	10.	0.	
25	0.	3.	5.	0.	
26	0.	4.	7.	0.	
27	0.	5.	6.	1.	
28	0.	5.	4.	0.	
29	0.	4.	8.	1.	
30	0.	6.	5.	0.	
31	0.	6.	4.	0.	
32	0.	2.	5.	0.	
33	0.	7.	4.	0.	
34	0.	5.	9.	0.	
35	0.	5.	10.	0.	
36	0.	6.	1.	0.	
37	0.	5.	10.	0.	
38	0.	3.	3.	0.	
39	1.	2.	7.	0.	
40	0.	2.	5.	0.	
41	0.	7.	3.	0.	
42	0.	3.	4.	0.	
43	0.	6.	4.	1.	
44	0.	6.	4.	0.	
45	0.	13.	4.	0.	
46	0.	6.	6.	0.	
47	0.	1.	4.	0.	
48	0.	5.	5.	0.	
49	0.	7.	5.	0.	
50	0.	2.	5.	0.	
51	0.	4.	3.	2.	
52	0.	5.	3.	1.	
53	0.	10.	8.	0.	
54	0.	7.	5.	1.	
55	0.	3.	7.	2.	
56	0.	5.	7.	0.	
57	0.	5.	3.	0.	
58	0.	5.	3.	1.	
59	0.	2.	5.	0.	
60	0.	1.	1.	0.	

MINUTES

76-39-A-12

TABLE A-13. FREQUENCY OF GIVEN TIME SEPARATION AT EXIT GATEWAY

E.BOUND :	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE	F.L. = 330
9	0.	0.	0.	0.	
10	0.	0.	0.	0.	
11	0.	0.	0.	0.	
12	0.	0.	0.	0.	
13	0.	0.	1.	0.	
14	0.	1.	0.	0.	
15	0.	0.	4.	0.	
16	0.	2.	5.	0.	
17	0.	2.	3.	0.	
18	1.	3.	5.	0.	
19	0.	7.	5.	0.	
20	0.	2.	9.	0.	
21	0.	5.	10.	1.	
22	0.	7.	9.	0.	
23	1.	4.	8.	0.	
24	0.	8.	9.	0.	
25	0.	5.	5.	0.	
26	0.	15.	12.	0.	
27	0.	12.	6.	0.	
28	1.	9.	9.	0.	
29	0.	10.	7.	0.	
30	0.	9.	8.	0.	
31	0.	6.	3.	0.	
32	0.	8.	6.	0.	
33	0.	8.	6.	0.	
34	1.	8.	8.	1.	
35	0.	8.	6.	0.	
36	0.	11.	6.	0.	
37	0.	6.	7.	0.	
38	0.	4.	4.	0.	
39	0.	4.	3.	0.	
40	0.	3.	5.	0.	
41	0.	13.	2.	0.	
42	0.	7.	4.	0.	
43	0.	6.	6.	0.	
44	0.	6.	3.	0.	
45	0.	4.	8.	0.	
46	0.	9.	9.	1.	
47	0.	6.	4.	0.	
48	0.	9.	10.	1.	
49	0.	6.	4.	0.	
50	0.	3.	11.	0.	
51	0.	5.	6.	1.	
52	0.	4.	7.	0.	
53	0.	4.	5.	0.	
54	0.	1.	3.	0.	
55	0.	8.	6.	0.	
56	1.	3.	2.	0.	
57	0.	3.	4.	0.	
58	0.	3.	5.	0.	
59	0.	7.	5.	1.	
60	1.	4.	4.	0.	

MINUTES

76-39-A-13

TABLE A-14. FREQUENCY OF GIVEN TIME SEPARATION AT EXIT GATEWAY

F.L. = 350

W.BOUND :	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE
9	0.	0.	1.	0.
10	0.	0.	0.	0.
11	0.	0.	0.	0.
12	0.	0.	0.	0.
13	0.	0.	1.	0.
14	0.	0.	1.	0.
15	1.	6.	14.	0.
16	0.	9.	12.	0.
17	0.	8.	19.	1.
18	5.	10.	25.	1.
19	0.	17.	19.	2.
20	1.	19.	27.	2.
21	2.	16.	29.	3.
22	0.	14.	25.	1.
23	1.	11.	24.	4.
24	1.	17.	20.	0.
25	1.	29.	25.	2.
26	2.	12.	25.	1.
27	1.	22.	34.	3.
28	1.	19.	29.	5.
29	1.	25.	31.	3.
30	4.	27.	25.	2.
31	2.	21.	23.	4.
32	1.	22.	25.	1.
33	1.	22.	18.	0.
34	0.	21.	20.	4.
35	3.	19.	28.	4.
36	0.	20.	24.	2.
37	1.	25.	13.	1.
38	1.	24.	19.	5.
39	2.	17.	17.	4.
40	0.	18.	20.	3.
41	0.	16.	16.	3.
42	2.	20.	15.	2.
43	0.	23.	13.	2.
44	0.	18.	15.	4.
45	1.	16.	21.	10.
46	1.	10.	26.	4.
47	3.	20.	15.	3.
48	1.	16.	13.	5.
49	3.	18.	11.	4.
50	2.	16.	19.	1.
51	1.	15.	13.	1.
52	0.	24.	12.	5.
53	1.	18.	11.	3.
54	0.	14.	16.	2.
55	3.	14.	18.	4.
56	3.	16.	18.	2.
57	0.	19.	11.	0.
58	0.	18.	6.	4.
59	1.	11.	12.	2.
60	0.	10.	18.	3.

MINUTES

76-39-A-14

TABLE A-15. FREQUENCY OF GIVEN TIME SEPARATION AT EXIT GATEWAY

E.BCLNC :	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE
9	C.	C.	C.	C.
10	0.	C.	C.	C.
11	0.	0.	C.	C.
12	0.	C.	1.	C.
13	C.	1.	C.	C.
14	0.	2.	0.	C.
15	0.	1.	13.	C.
16	1.	7.	2C.	C.
17	1.	8.	21.	0.
18	0.	10.	23.	2.
19	1.	7.	25.	C.
20	0.	18.	33.	0.
21	1.	23.	32.	1.
22	0.	12.	45.	0.
23	0.	17.	35.	1.
24	0.	24.	35.	1.
25	0.	20.	37.	2.
26	C.	21.	42.	1.
27	1.	20.	46.	1.
28	0.	15.	38.	1.
29	2.	16.	33.	C.
30	0.	8.	18.	C.
31	C.	17.	3C.	C.
32	0.	16.	19.	1.
33	1.	9.	3C.	2.
34	0.	19.	25.	2.
35	C.	1C.	2C.	1.
36	2.	27.	22.	C.
37	1.	25.	16.	1.
38	0.	16.	16.	2.
39	C.	13.	31.	4.
40	C.	14.	9.	2.
41	0.	18.	17.	1.
42	0.	23.	3C.	C.
43	1.	16.	17.	2.
44	0.	13.	14.	0.
45	1.	16.	14.	4.
46	1.	13.	25.	1.
47	1.	19.	2C.	1.
48	C.	16.	17.	C.
49	C.	13.	14.	1.
50	C.	17.	16.	1.
51	C.	14.	17.	2.
52	C.	16.	12.	1.
53	0.	14.	11.	2.
54	C.	16.	13.	1.
55	C.	15.	15.	1.
56	0.	18.	14.	0.
57	1.	19.	7.	C.
58	0.	14.	17.	0.
59	C.	12.	14.	2.
60	1.	13.	11.	0.

F.L. = 37C

MINUTES

76-39-A-15

TABLE A-16. FREQUENCY OF GIVEN TIME SEPARATION AT EXIT GATEWAY

N.BCLNC I	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE	F.L. = 390
9	0.	0.	0.	0.	
10	0.	0.	0.	0.	
11	0.	0.	0.	0.	
12	0.	0.	0.	0.	
13	0.	1.	0.	0.	
14	0.	0.	1.	0.	
15	0.	2.	2.	0.	
16	0.	2.	0.	0.	
17	0.	1.	1.	0.	
18	0.	2.	0.	0.	
19	1.	1.	0.	0.	
20	0.	2.	0.	0.	
21	0.	2.	2.	0.	
22	0.	4.	1.	0.	
23	0.	4.	1.	0.	
24	0.	3.	0.	0.	
25	0.	4.	1.	0.	
26	0.	2.	1.	0.	
27	0.	7.	3.	0.	
28	1.	3.	0.	0.	
29	0.	7.	1.	0.	
30	0.	4.	0.	0.	
31	0.	2.	0.	0.	
32	0.	3.	1.	0.	
33	0.	5.	0.	0.	
34	0.	5.	1.	0.	
35	0.	7.	1.	0.	
36	0.	3.	0.	0.	
37	0.	2.	2.	1.	
38	0.	2.	1.	0.	
39	0.	7.	0.	0.	
40	0.	5.	0.	0.	
41	0.	7.	1.	0.	
42	1.	6.	0.	0.	
43	0.	2.	1.	0.	
44	0.	3.	0.	0.	
45	0.	5.	0.	0.	
46	0.	4.	0.	0.	
47	0.	2.	0.	0.	
48	0.	3.	0.	0.	
49	0.	4.	0.	0.	
50	0.	3.	1.	0.	
51	0.	5.	0.	0.	
52	0.	3.	0.	0.	
53	1.	1.	0.	0.	
54	1.	2.	0.	0.	
55	0.	2.	1.	0.	
56	0.	1.	0.	0.	
57	0.	3.	0.	0.	
58	0.	4.	0.	0.	
59	1.	4.	0.	0.	
60	0.	2.	1.	0.	

MINUTES

76-39-A-16

TABLE A-17. FREQUENCY OF GIVEN TIME SEPARATION AT EXIT GATEWAY

MINUTES

E.BCLAC :	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE	F.L. = 410
9	0.	0.	0.	0.	
10	0.	0.	0.	0.	
11	0.	0.	0.	0.	
12	0.	0.	0.	0.	
13	0.	0.	0.	0.	
14	0.	0.	0.	0.	
15	0.	0.	0.	0.	
16	0.	0.	0.	0.	
17	0.	0.	0.	0.	
18	0.	0.	0.	0.	
19	0.	0.	0.	0.	
20	0.	0.	0.	0.	
21	0.	0.	0.	0.	
22	0.	0.	0.	0.	
23	0.	0.	0.	0.	
24	0.	1.	0.	0.	
25	0.	0.	0.	0.	
26	0.	0.	0.	0.	
27	0.	0.	0.	0.	
28	0.	0.	0.	0.	
29	0.	0.	0.	0.	
30	0.	0.	0.	0.	
31	0.	0.	0.	0.	
32	0.	1.	0.	0.	
33	0.	0.	0.	0.	
34	0.	0.	0.	0.	
35	0.	0.	0.	0.	
36	0.	0.	0.	0.	
37	0.	0.	0.	0.	
38	0.	0.	0.	0.	
39	0.	1.	0.	0.	
40	0.	0.	0.	0.	
41	0.	0.	0.	0.	
42	0.	0.	0.	0.	
43	0.	0.	0.	0.	
44	0.	0.	0.	0.	
45	0.	0.	0.	0.	
46	0.	0.	0.	0.	
47	0.	0.	0.	0.	
48	0.	0.	0.	0.	
49	0.	0.	0.	0.	
50	0.	0.	0.	0.	
51	0.	0.	0.	0.	
52	0.	0.	0.	0.	
53	0.	0.	0.	0.	
54	0.	0.	0.	0.	
55	0.	0.	0.	0.	
56	0.	0.	0.	0.	
57	0.	0.	1.	0.	
58	0.	0.	0.	0.	
59	0.	1.	0.	0.	
60	0.	0.	0.	0.	

76-39-A-17

TABLE A-18. FREQUENCY OF GIVEN TIME SEPARATION AT EXIT GATEWAY

MINUTES

N.DELAY I	N. ROUTE	A. ROUTE	B. ROUTE	S. ROUTE	F.L. = 430
9	0.	0.	0.	0.	
10	0.	0.	0.	0.	
11	0.	0.	0.	0.	
12	0.	0.	0.	0.	
13	0.	0.	0.	0.	
14	0.	0.	0.	0.	
15	0.	0.	0.	0.	
16	0.	0.	0.	0.	
17	0.	0.	0.	0.	
18	0.	0.	0.	0.	
19	0.	0.	0.	0.	
20	0.	0.	0.	0.	
21	0.	0.	0.	0.	
22	0.	0.	0.	0.	
23	0.	0.	0.	0.	
24	0.	0.	0.	0.	
25	0.	0.	0.	0.	
26	0.	0.	0.	0.	
27	0.	0.	0.	0.	
28	0.	0.	0.	0.	
29	0.	0.	0.	0.	
30	0.	0.	0.	0.	
31	0.	0.	0.	0.	
32	0.	0.	0.	0.	
33	0.	0.	0.	0.	
34	0.	0.	0.	0.	
35	0.	0.	0.	0.	
36	0.	0.	0.	0.	
37	0.	0.	0.	0.	
38	0.	0.	0.	0.	
39	0.	0.	0.	0.	
40	0.	0.	0.	0.	
41	0.	0.	0.	0.	
42	0.	0.	0.	0.	
43	0.	0.	0.	0.	
44	0.	0.	0.	0.	
45	0.	0.	0.	0.	
46	0.	0.	0.	0.	
47	0.	0.	0.	0.	
48	0.	0.	0.	0.	
49	0.	0.	0.	0.	
50	0.	0.	0.	0.	
51	0.	0.	0.	0.	
52	0.	0.	0.	0.	
53	0.	0.	0.	0.	
54	0.	0.	0.	0.	
55	0.	0.	0.	0.	
56	0.	0.	0.	0.	
57	0.	2.	0.	0.	
58	0.	0.	0.	0.	
59	0.	0.	0.	0.	
60	0.	0.	0.	0.	

76-39-A-18

APPENDIX B

CHANGE-IN-SEPARATION TABLES (AIRCRAFT PAIRS WITH MACH SPEED DIFFERENCES FROM -.10 TO .10)

TABLE B-1

```
DIRECTION = EASTBOUND        MACH DIFFERENCE =  0       NUMBER OF A/C PAIRS = 571

            1   2          3          4          5          6
            4567890123456789012345678901234567890123456789012345678901234567890
       8                                    1    1    1 1          8
       7        1                        3       11                7
       6                          1                                6
       5      13121 1 1    1 1   1111           1              1   5
       4        2    2 4  4   2      12        1 1        1 1  1   4
       3    11     11 1 11  1 12     1      2 31     1             3
       2   121   413641222 2421 1 32111 3  1  22 212 232 1         2
       1      12245122152233422214521 31 4 32 211 1 11311222       1
       C     8652427266172 1111   334332445322423121232223132      0
      -1      237452442 41443 1123 31142 2 216222232    3 211      -1
      -2        12131121442  32133214111  1 1 122 21 11 11         -2
      -3         31     12   121   1    11  2    111   1  1        -3
      -4      1   1 2 1 1     22 1 211          2  11 1            -4
      -5          1    1    1  11  2  1      1 1 1                 -5
      -6                     1              1 2          1         -6
      -7                 11                                1       -7
      -8                                1                          -8
      -9                                                           -9
     -10                              1                            -10
            1   2          3          4          5          6
            4567890123456789012345678901234567890123456789012345678901234567890
                      INITIAL SEPARATION (MINUTES)
```

CHANGE IN SEPARATION (MINUTES)

76-39-B-1

TABLE B-2

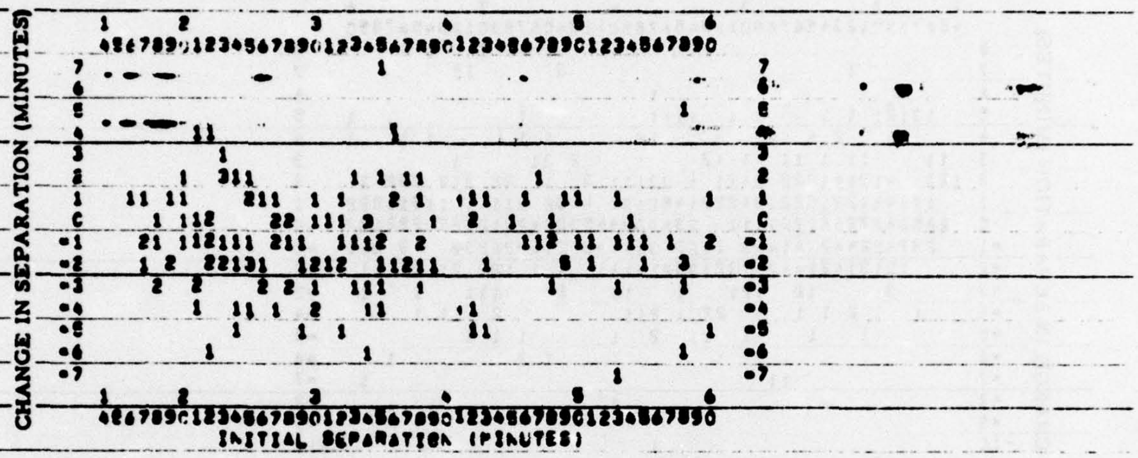
```
DIRECTION = WESTBOUND        MACH DIFFERENCE =  0       NUMBER OF A/C PAIRS = 670

            1   2          3          4          5          6
            4567890123456789012345678901234567890123456789012345678901234567890
      11                                  1         1              11
      10                               1                           10
       9        2    1                                             9
       8          1      1                      1                  8
       7       1  1                        1 1             1       7
       6       41 11 1        1               1     1      1       6
       5       22 11    1     1 12            1    2 1 1           5
       4    1  112321 21 1  2 1 1    11       1 1  2   1 1    11   4
       3   112 1   13241213 1221 13   11 2 1 121121     1211       3
       2     31461312 21 422 122232 2 1  11 21   3113211  2 1      2
       1   114332842481421561 222   13 232 21 1 212 2211133        1
       C    18432534214353 4222 6423512 3 112243 11 112 311        0
      -1      4233732222733244434232 4 22322223312 13 3114126      -1
      -2          23 3211 313315121421 22121121   1 12 1 11        -2
      -3         1241   111 133231     111111131 11       1111 1   -3
      -4      1  1121111121    11 1   1        1     11            -4
      -5          11      1  1    12        2 2    2     1 1       -5
      -6    1        1         1       2  1          1             -6
      -7              1              11           1                -7
      -8                                       1         1         -8
      -9                    1       1    1   11          1         -9
     -10                   1        1                  1    1      -10
     -11                        1                                  -11
     -12                                          1                -12
            1   2          3          4          5          6
            4567890123456789012345678901234567890123456789012345678901234567890
                      INITIAL SEPARATION (MINUTES)
```

CHANGE IN SEPARATION (MINUTES)

76-39-B-2

TABLE B-3

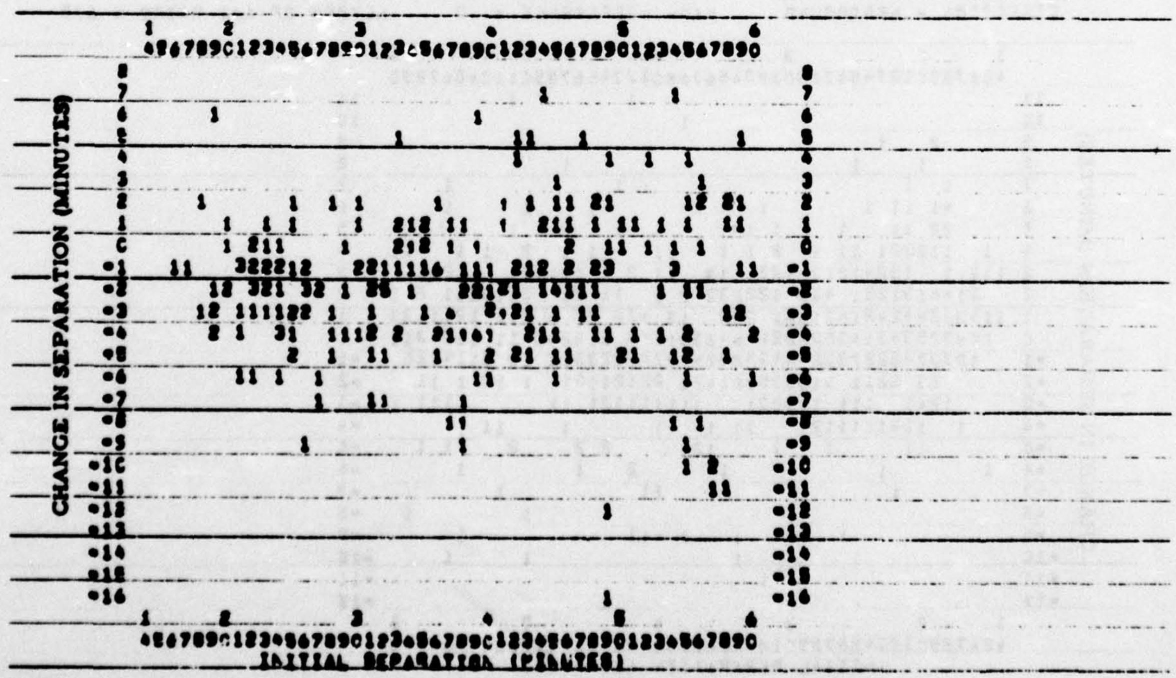
DIRECTION = EASTBOUND MACH DIFFERENCE = .01 NUMBER OF A/C PAIRS = 163



76-39-B-3

TABLE B-4

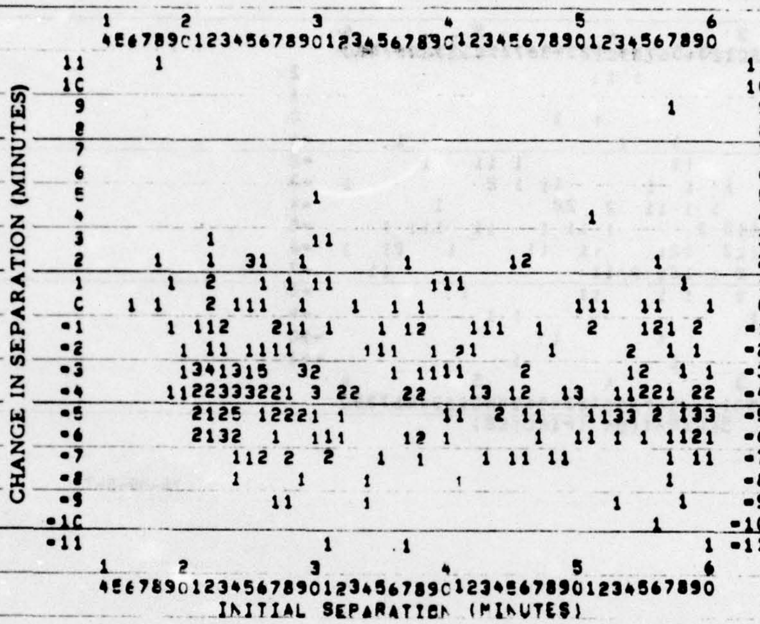
DIRECTION = WESTBOUND MACH DIFFERENCE = .01 NUMBER OF A/C PAIRS = 279



76-39-B-4

TABLE B-5

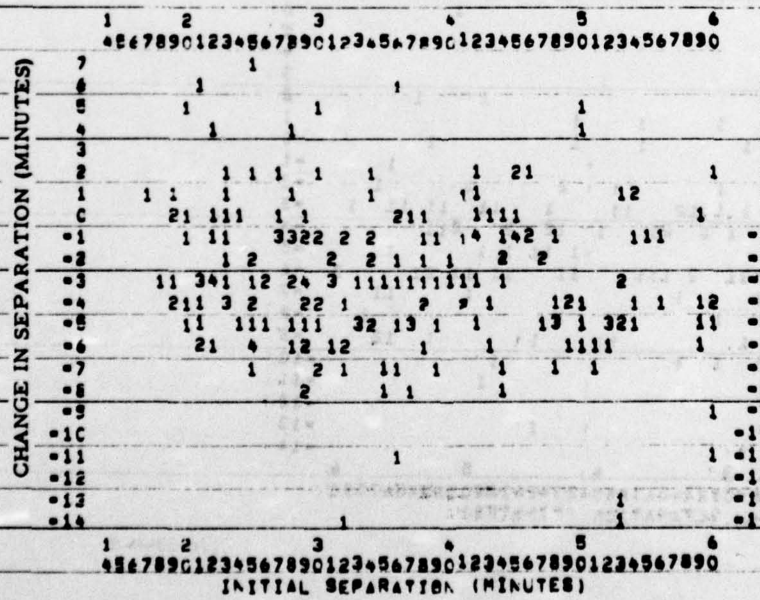
CIRECTION = EASTBOUNC   MACH CIFFERENCE = .02   NUMBER OF A/C PAIRS = 280



76-39-B-5

TABLE B-6

CIRECTION = WESTBOUNC   MACH CIFFERENCE = .02   NUMBER OF A/C PAIRS = 231



76-39-B-6

TABLE B-7

```
CIRECTION = EASTBOUND        MACH CIFFERENCE =.03        NUMBER OF A/C PAIRS = 114

     1     2         3         4         5         6
     45678901234567890123456789C12345678901234567890
  2            1  1          1 1                      2
  1                                                   1
  C                               1  1                  C
 -1                          1   1                1      -1
 -2                         11           1 11   1        -2
 -3                1 1   1  1  1      11 1 2          1  -3
 -4               21 1    1 1 11  2  22        1         -4
 -5                 1 2112 2      1 11 1   11  111 1     -5
 -6               1 111113  121    11  11     1   21  1  -6
 -7              1   1  2 1 321 2 11               11    -7
 -8              1      1   1 1    11        1           -8
 -9                    1                 1 1             -9
-10             1             1       1                  -10
-11                          1           1               -11
     1     2         3         4         5         6
     45678901234567890123456789012345678901234567890
              INITIAL SEPARATION (MINUTES)
```

CHANGE IN SEPARATION (MINUTES)

76-39-B-7

TABLE B-8

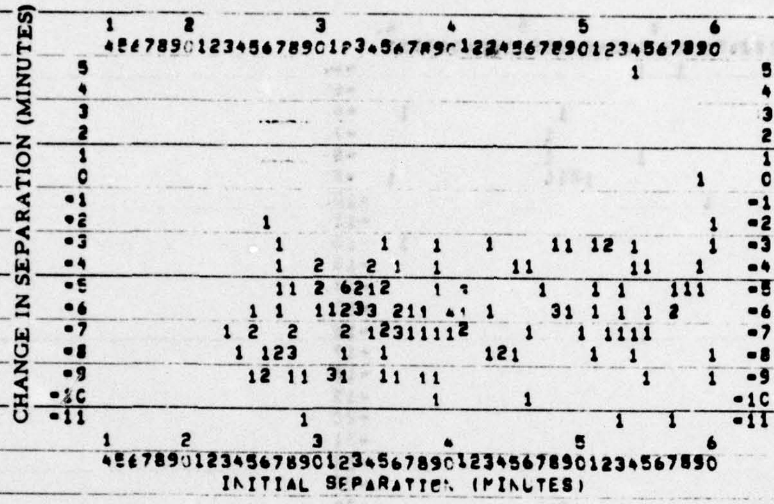
```
CIRECTION = WESTBOUND        MACH CIFFERENCE =.03        NUMBER OF A/C PAIRS = 131

     1     2         3         4         5         6
     45678901234567890123456789012345678901234567890
  6                                       1           6
  5                                                   5
  4                                                   4
  3               1            1                      3
  2                                       1    1        2
  1                      1     1    1                   1
  C                    1       1    1          1         C
 -1                                1              1      -1
 -2          12 1     1       1 1 2      1      1     -2
 -3      1 1  1  1  1 1 12   11    1   11  11 11  1   -3
 -4          111 1   1 1  21   1  12  2   211         -4
 -5                1               11 11 1 1      1      -5
 -6          2 1   131  2 111    11   11 11 21     2  -6
 -7          1 11141     1               1     11     -7
 -8                       1           1              1    -8
 -9                   2 1         11    1       1  12     -9
-10                   1  1  1             1              -10
-11                                1       1             -11
-12                 1                                     -12
-13                                1   1                 -13
-14                     1                                 -14
     1     2         3         4         5         6
     456789C1234567890123456789C12345678901234567890
              INITIAL SEPARATION (MINUTES)
```

CHANGE IN SEPARATION (MINUTES)

76-39-B-8

TABLE B-9

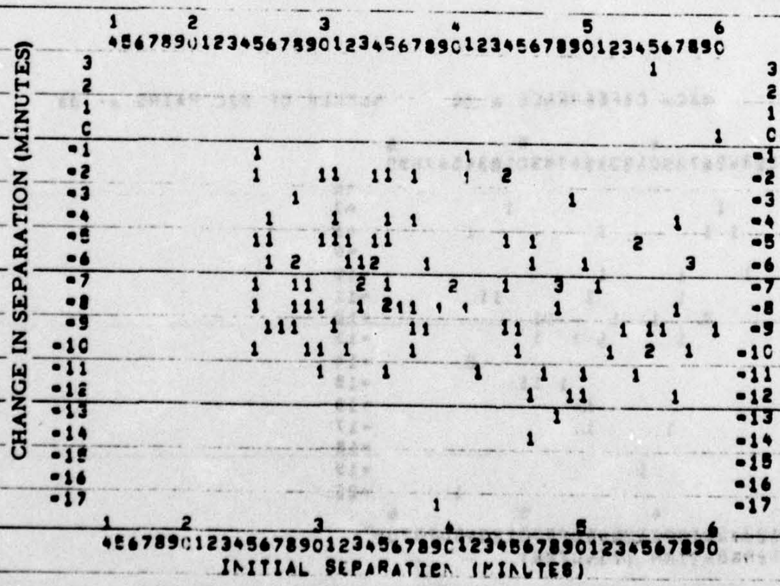
DIRECTION = EASTBOUND   MACH DIFFERENCE = .04   NUMBER OF A/C PAIRS = 167



76-39-B-9

TABLE B-10

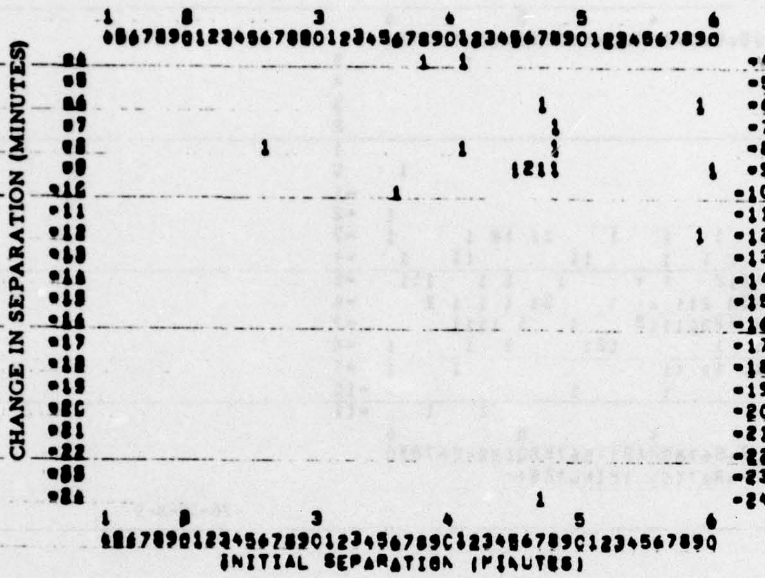
DIRECTION = WESTBOUND   MACH DIFFERENCE = .04   NUMBER OF A/C PAIRS = 105



76-39-B-10

TABLE B-11

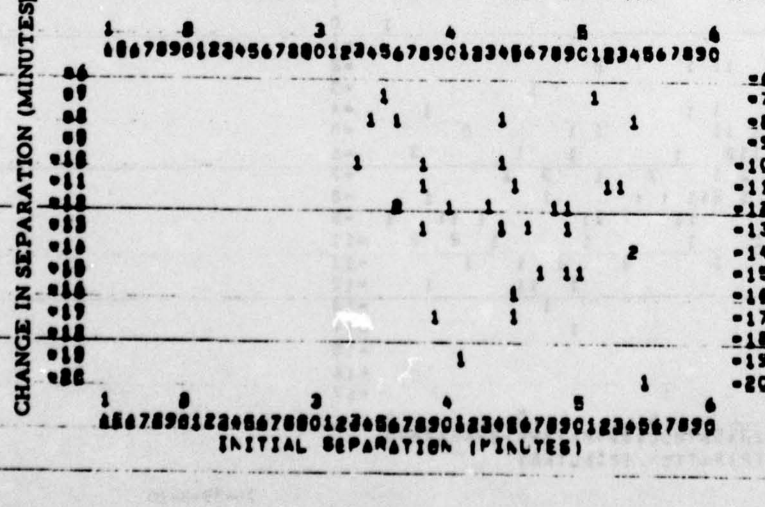
DIRECTION = E&W BOUND MACH DIFFERENCE = .05 NUMBER OF A/C PAIRS = 17



76-39-B-11

TABLE B-12

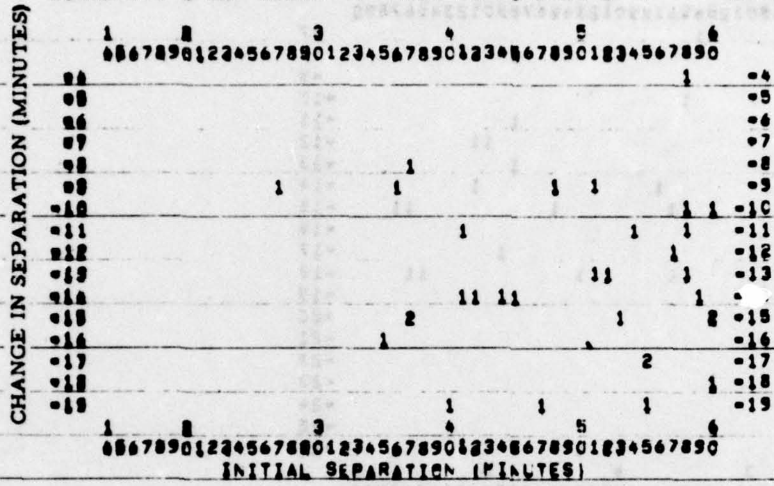
DIRECTION = E&W BOUND MACH DIFFERENCE = .04 NUMBER OF A/C PAIRS = 30



76-39-B-12

TABLE B-13

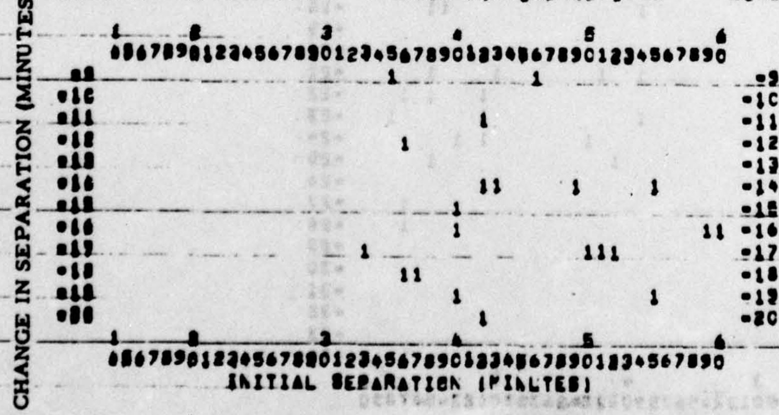
DIRECTION = E&W BOUND   MACH DIFFERENCE = .07   NUMBER OF A/C PAIRS = 32



76-39-B-13

TABLE B-14

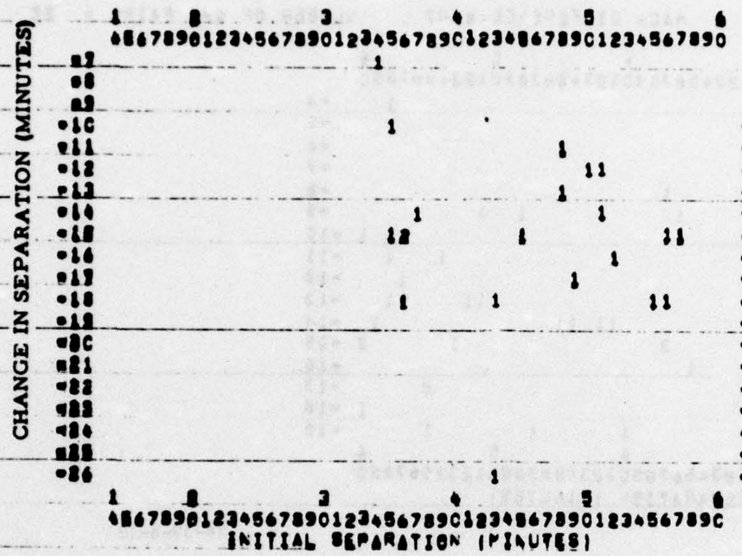
DIRECTION = E&W BOUND   MACH DIFFERENCE = .08   NUMBER OF A/C PAIRS = 21



76-39-B-14

TABLE B-15

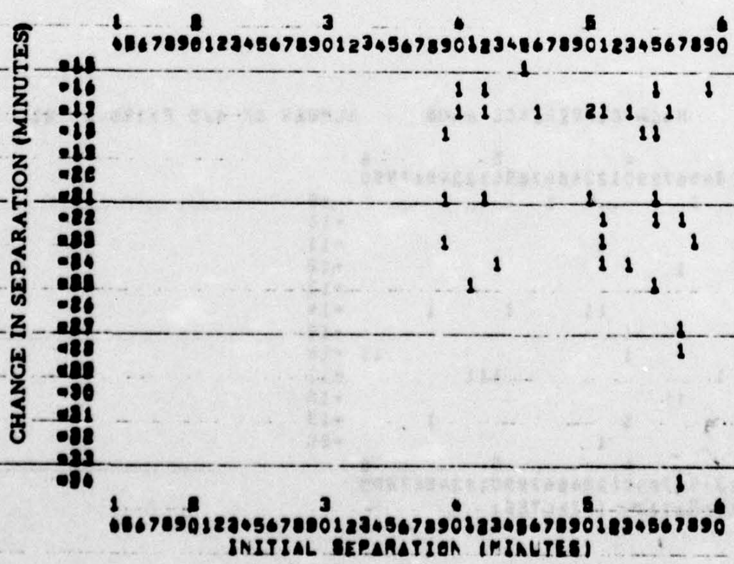
DIRECTION = E&W BOUND MACH DIFFERENCE = .09 NUMBER OF A/C PAIRS = 21



76-39-B-15

TABLE B-16

DIRECTION = E&W BOUND MACH DIFFERENCE = .10 NUMBER OF A/C PAIRS = 30



76-39-B-16

TABLE B-17

DIRECTION = EASTBOUND   MACH DIFFERENCE = -.01   NUMBER OF A/C PAIRS = 287

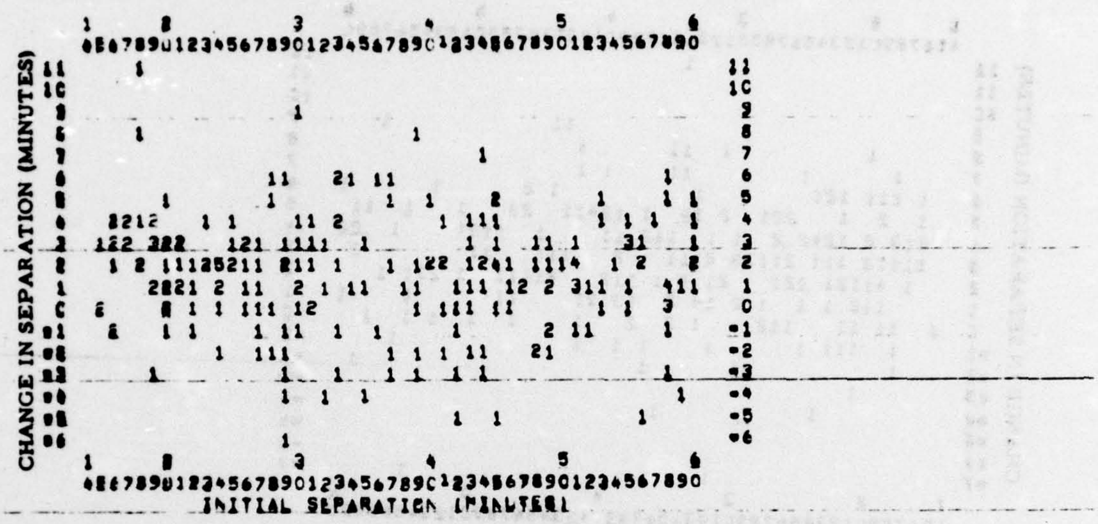


TABLE B-18

DIRECTION = WESTBOUND   MACH DIFFERENCE = -.01   NUMBER OF A/C PAIRS = 218

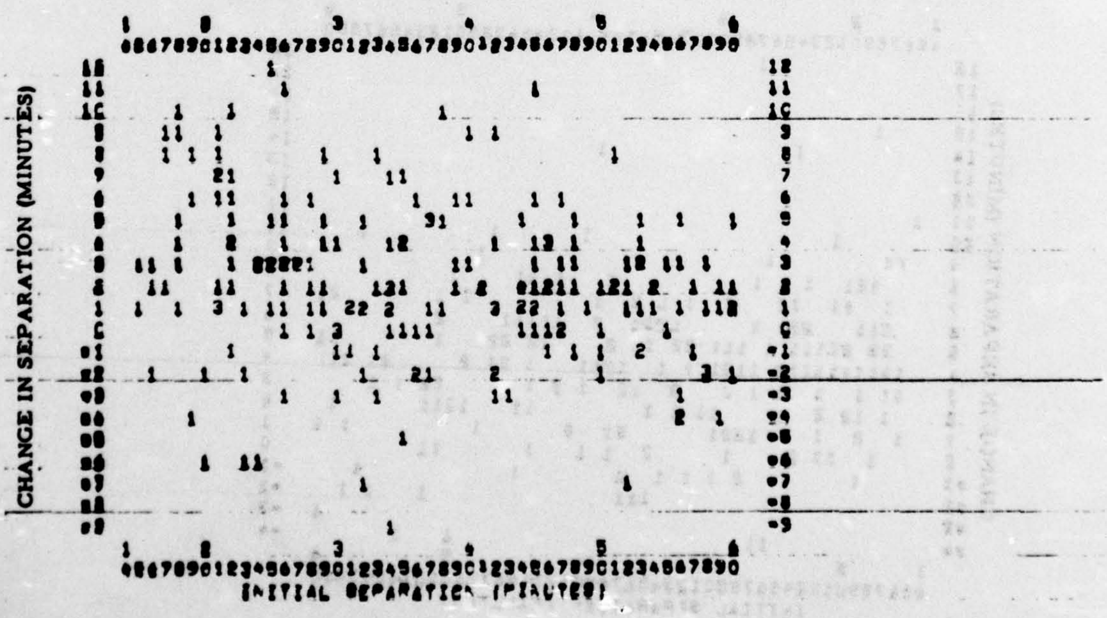


TABLE B-19

DIRECTION = EASTBOUND   MACH DIFFERENCE = -.02   NUMBER OF A/C PAIRS = 244

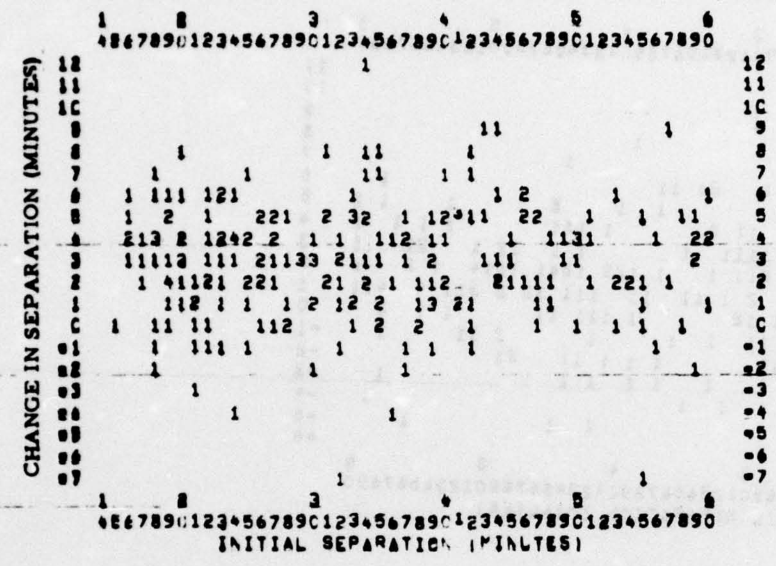


TABLE B-20

DIRECTION = WESTBOUND   MACH DIFFERENCE = -.02   NUMBER OF A/C PAIRS = 232

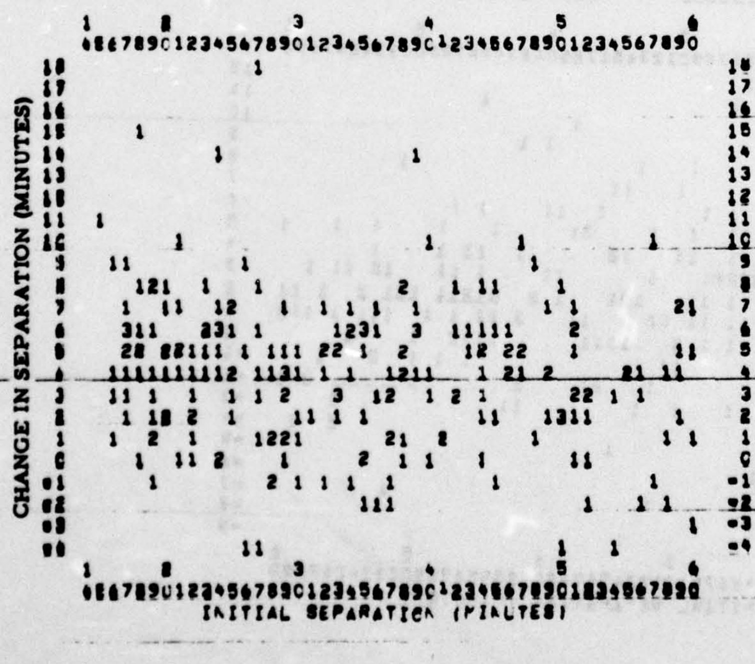


TABLE B-21

DIRECTION = EASTBOUND   MACH DIFFERENCE = -.03   NUMBER OF A/C PAIRS = 207

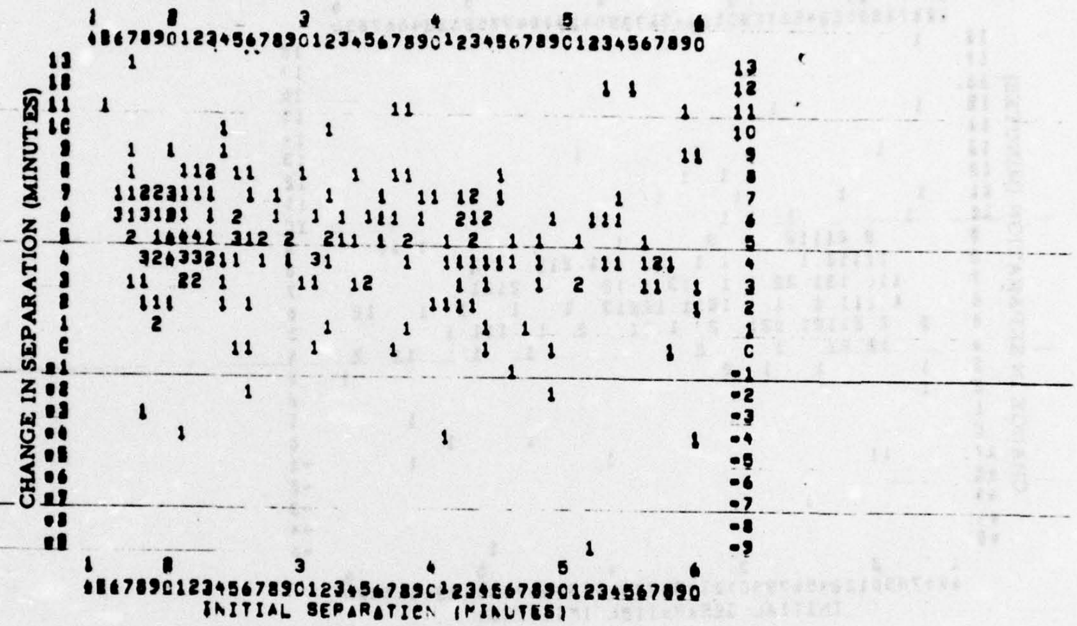


TABLE B-22

DIRECTION = WESTBOUND   MACH DIFFERENCE = -.03   NUMBER OF A/C PAIRS = 182

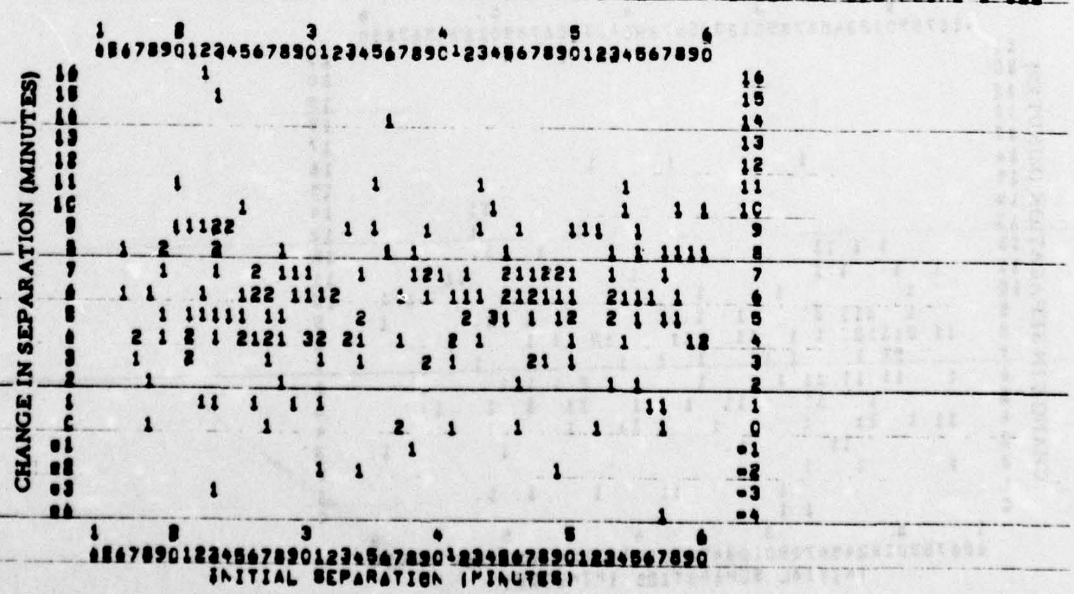


TABLE B-23

DIRECTION = EASTBOUND   MACH DIFFERENCE = -.04   NUMBER OF A/C PAIRS = 174

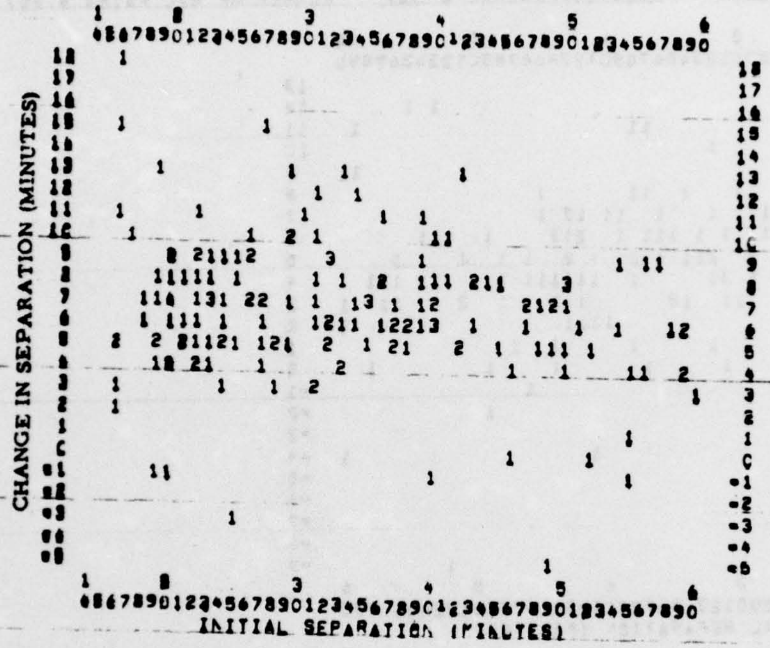


TABLE B-24

DIRECTION = WESTBOUND   MACH DIFFERENCE = -.04   NUMBER OF A/C PAIRS = 133

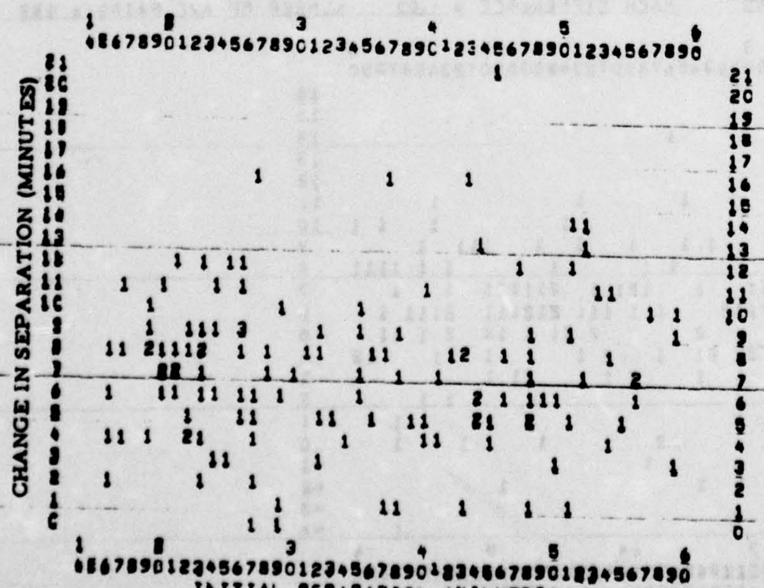


TABLE B-25

DIRECTION = E&W BOUND   MACH DIFFERENCE = -.05   NUMBER OF A/C PAIRS = 81

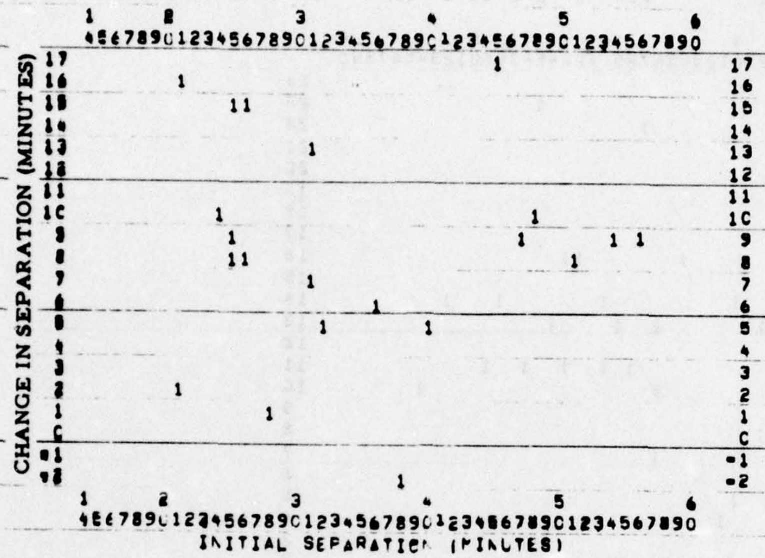


TABLE B-26

DIRECTION = E&W BOUND   MACH DIFFERENCE = -.06   NUMBER OF A/C PAIRS = 56

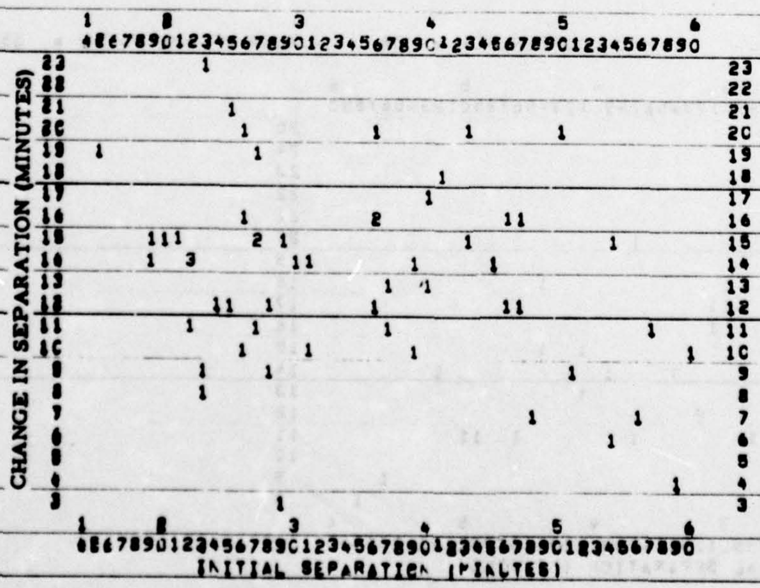


TABLE B-27

DIRECTION = E&W BOUND   MACH DIFFERENCE = -.07   NUMBER OF A/C PAIRS = 41

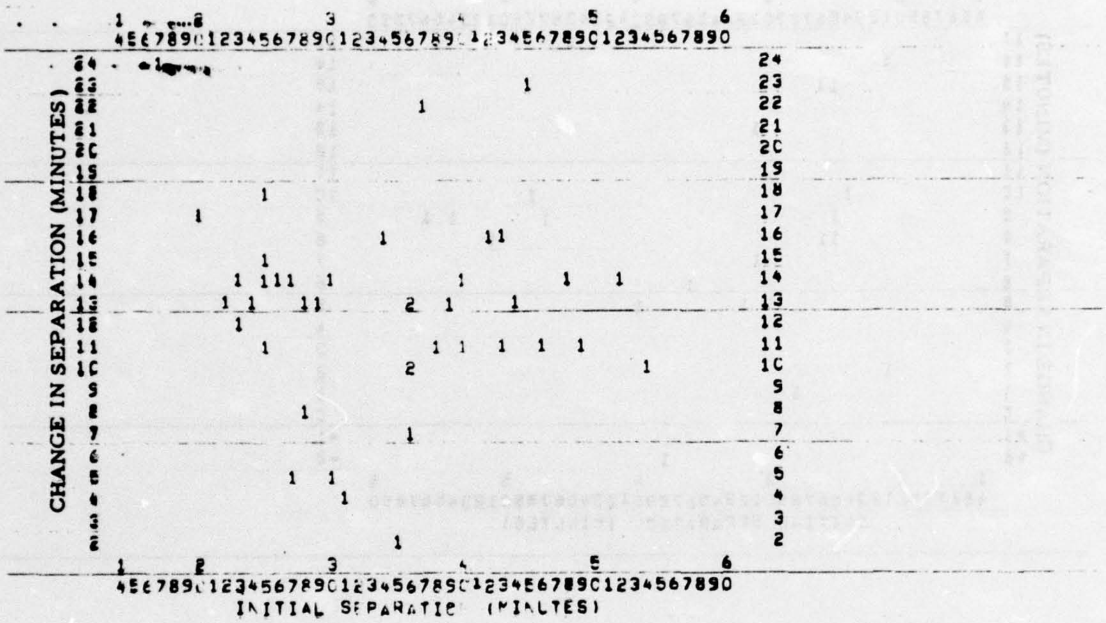


TABLE B-28

DIRECTION = E&W BOUND   MACH DIFFERENCE = -.08   NUMBER OF A/C PAIRS = 35

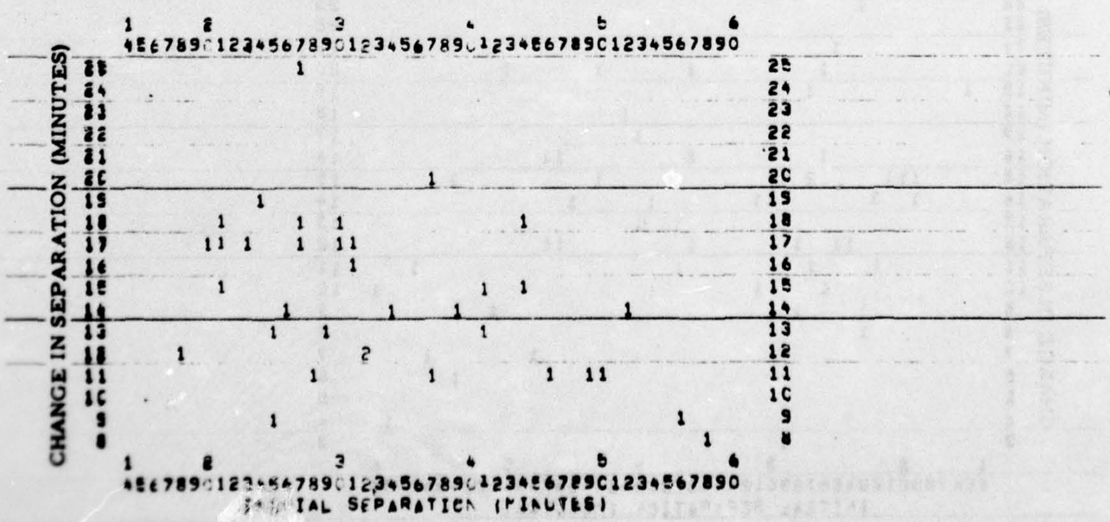


TABLE B-29

DIRECTION = E&W BOUND   MACH DIFFERENCE = -.09   NUMBER OF A/C PAIRS = 15

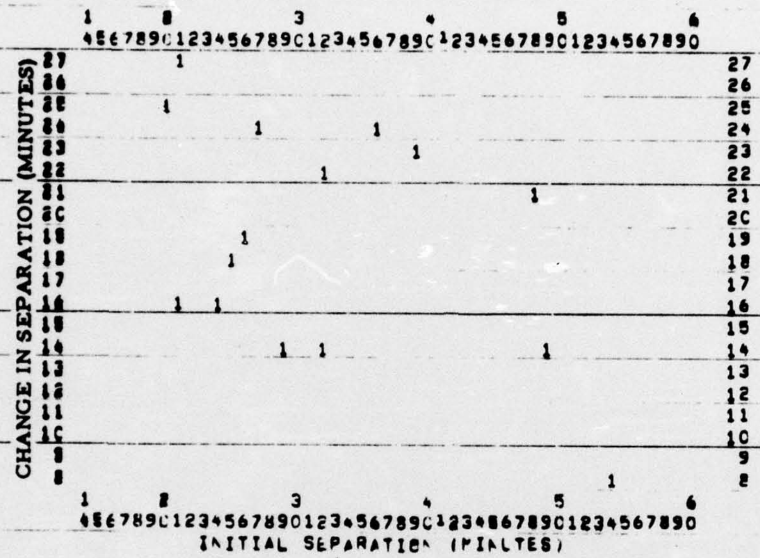
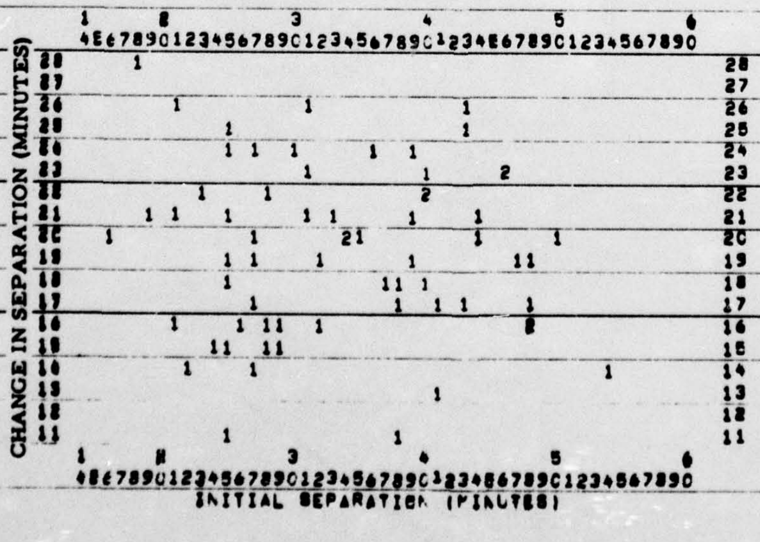


TABLE B-30

DIRECTION = E&W BOUND   MACH DIFFERENCE = -.10   NUMBER OF A/C PAIRS = 65



APPENDIX C

CHANGE-IN-SEPARATION HISTOGRAMS (RAW DATA FREQUENCIES)

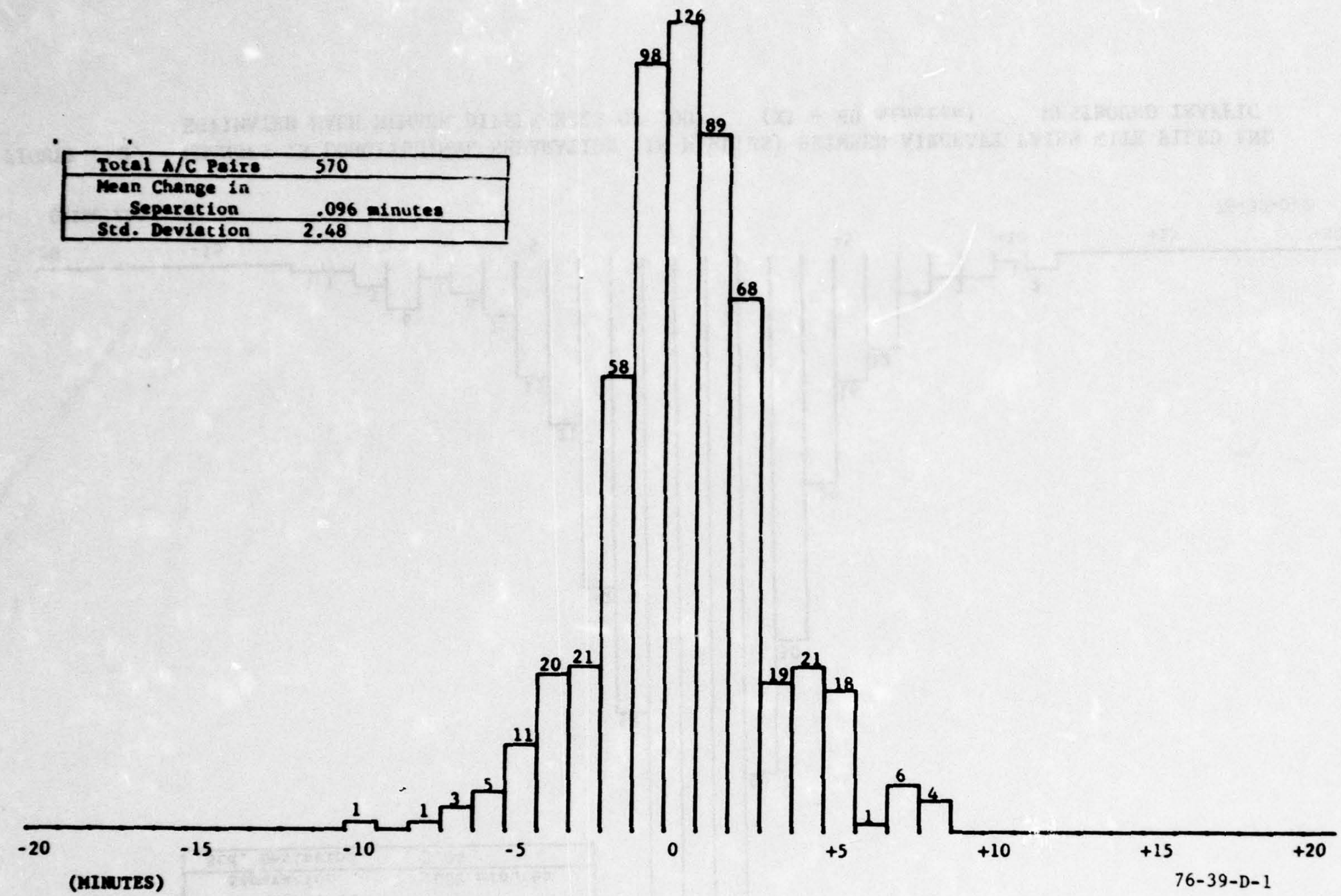


FIGURE C-1. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS AND FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF .00 (X1 - 60 minutes) EASTBOUND TRAFFIC

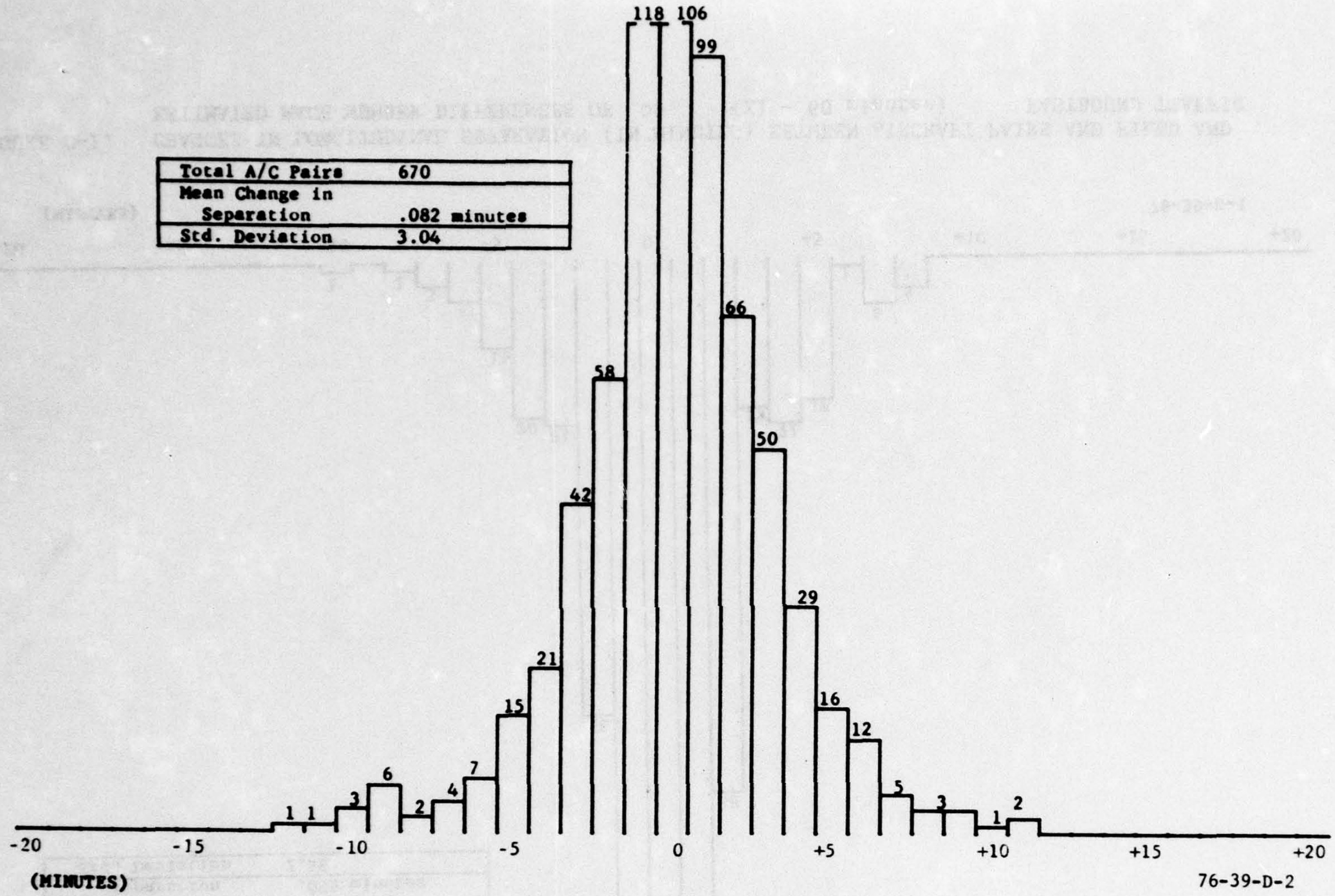


FIGURE C-2. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF .00 (X1 - 60 minutes) WESTBOUND TRAFFIC

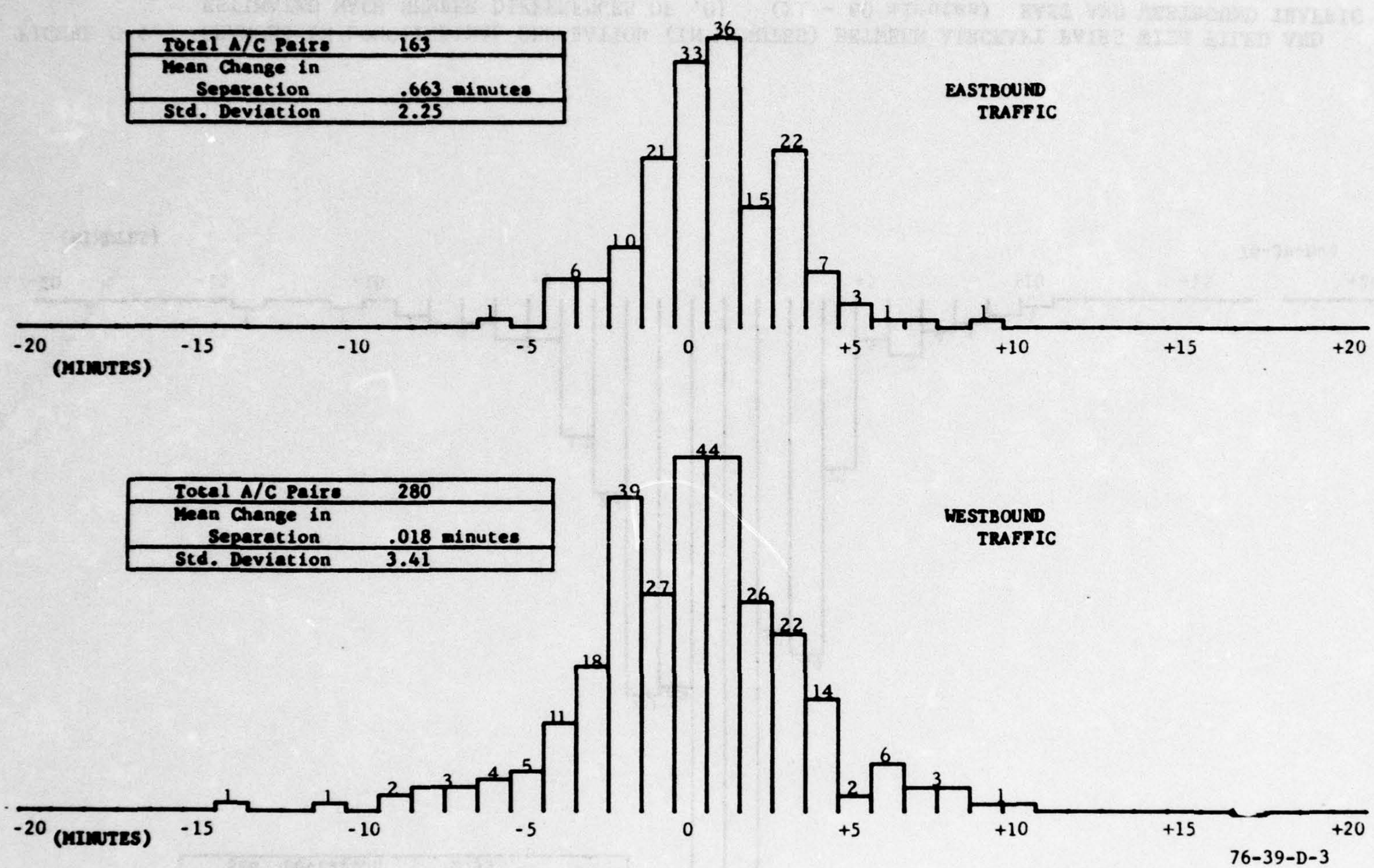


FIGURE C-3. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF .01 (X1 - 60 minutes)

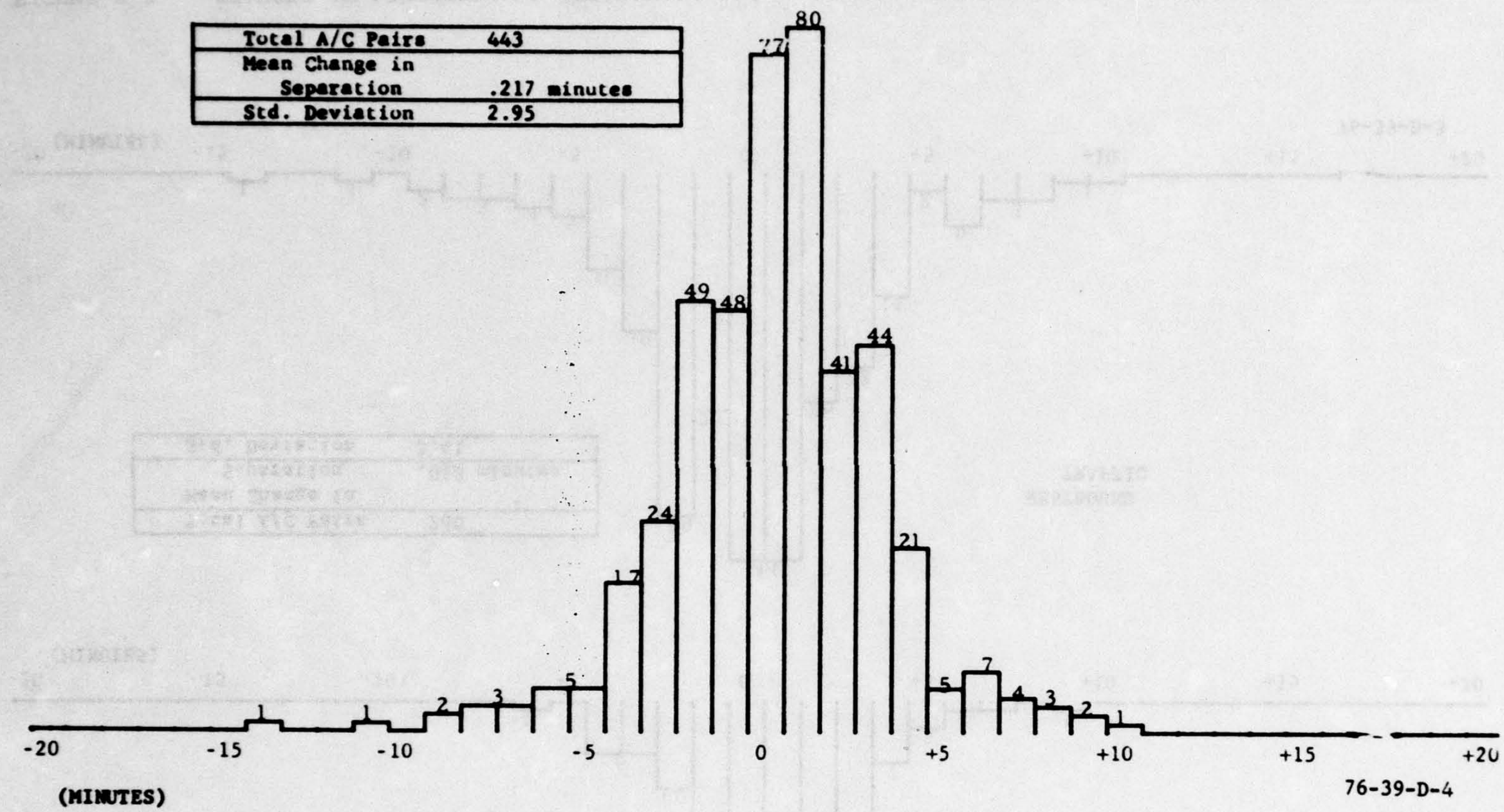


FIGURE C-4. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF .01 (X1 - 60 minutes) EAST AND WESTBOUND TRAFFIC

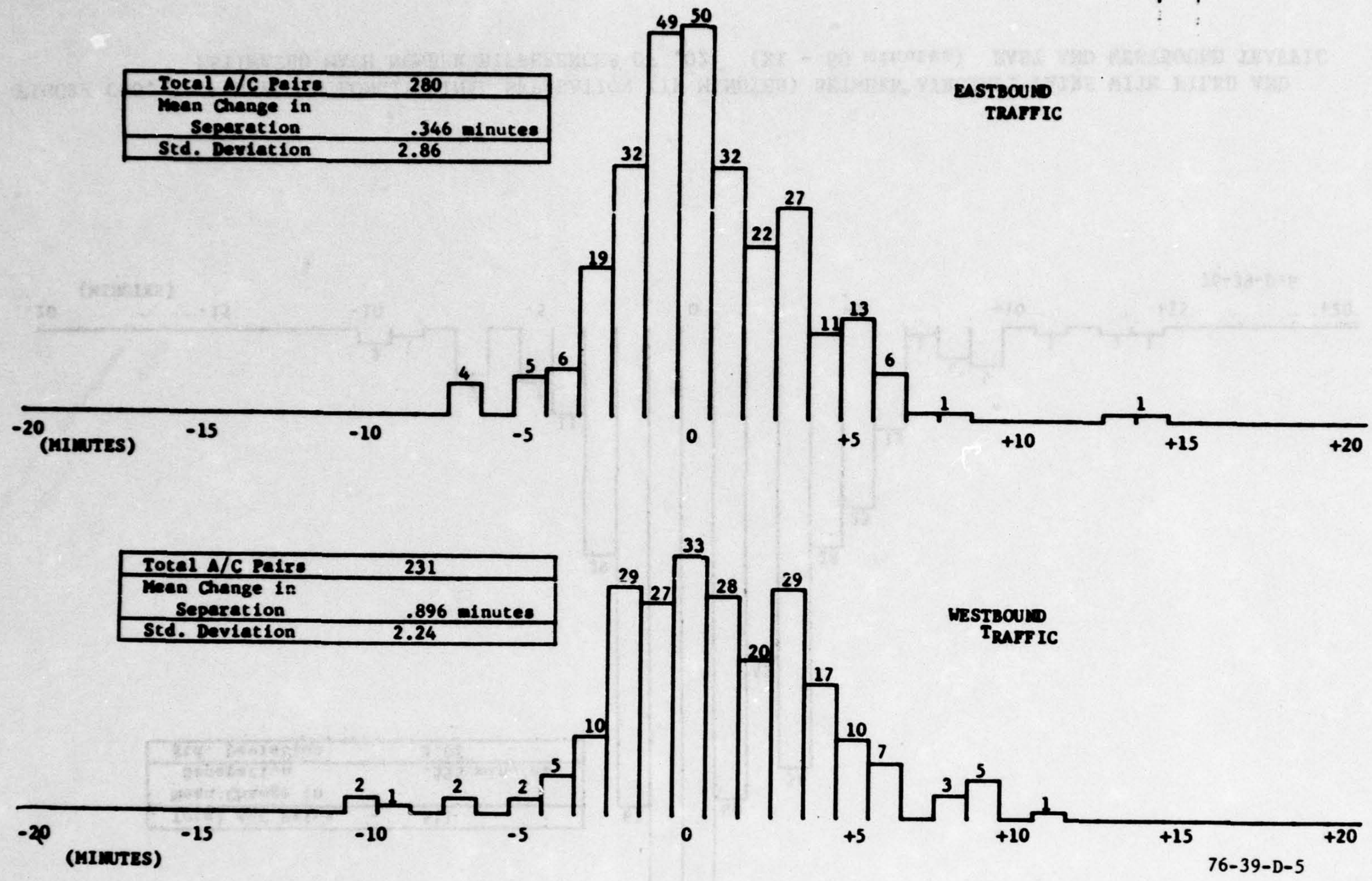


FIGURE C-5. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF .02 (X1 - 60 minutes)

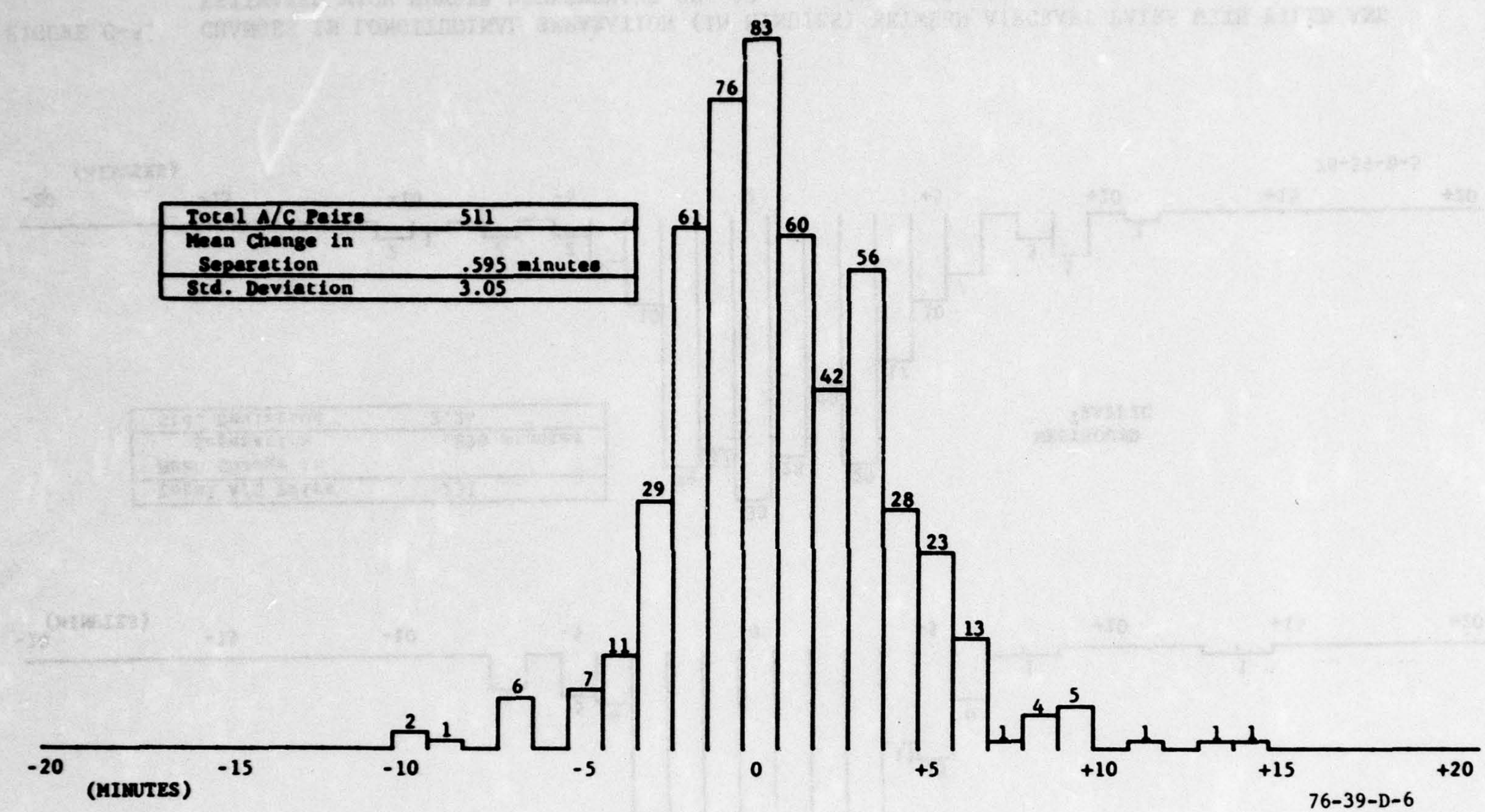


FIGURE C-6. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF .02 (X1 - 60 minutes) EAST AND WESTBOUND TRAFFIC

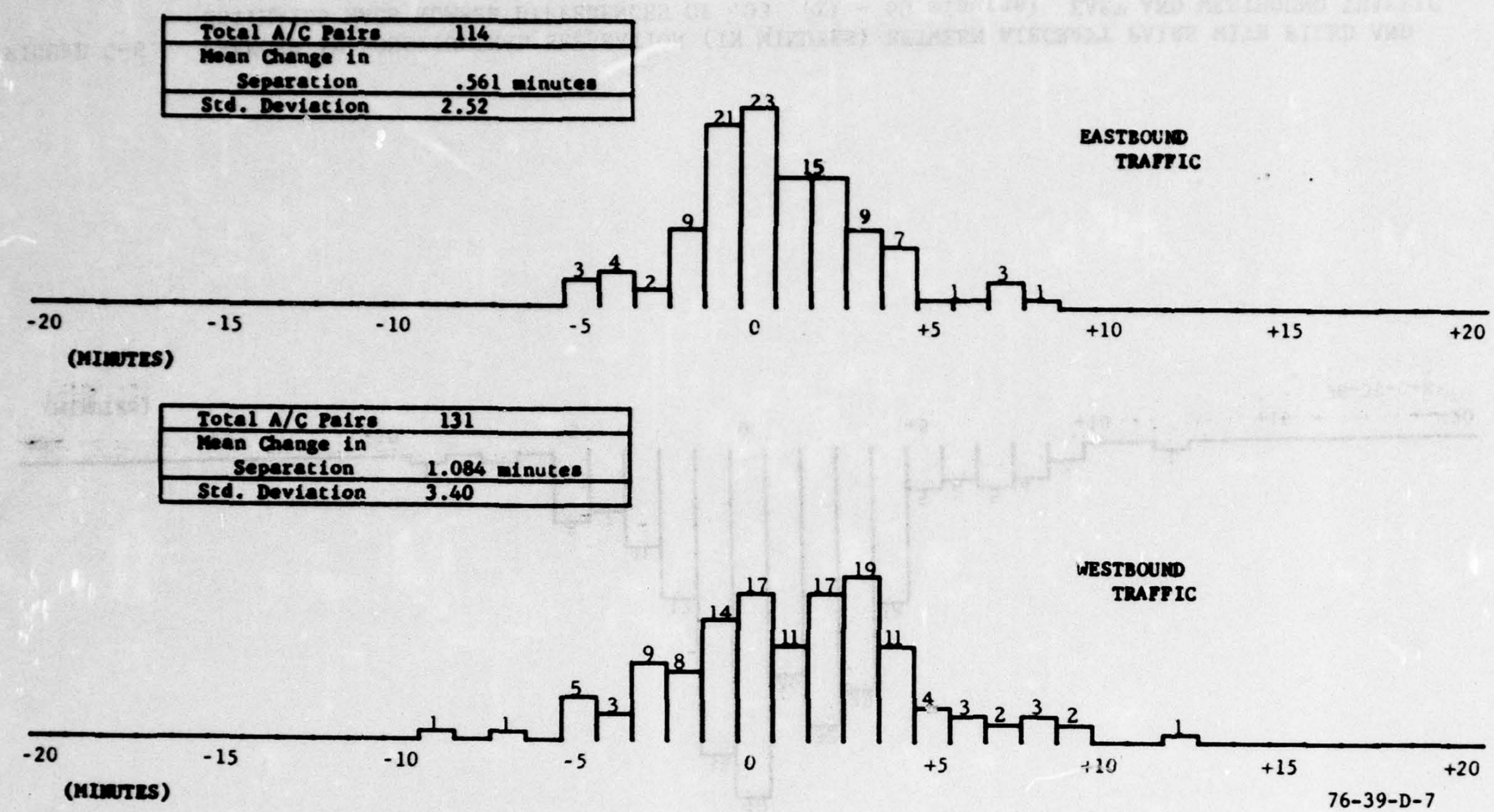


FIGURE C-7. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF .03 (X1 - 60 minutes)

Total A/C Pairs	245
Mean Change in Separation	.841 minutes
Std. Deviation	3.03

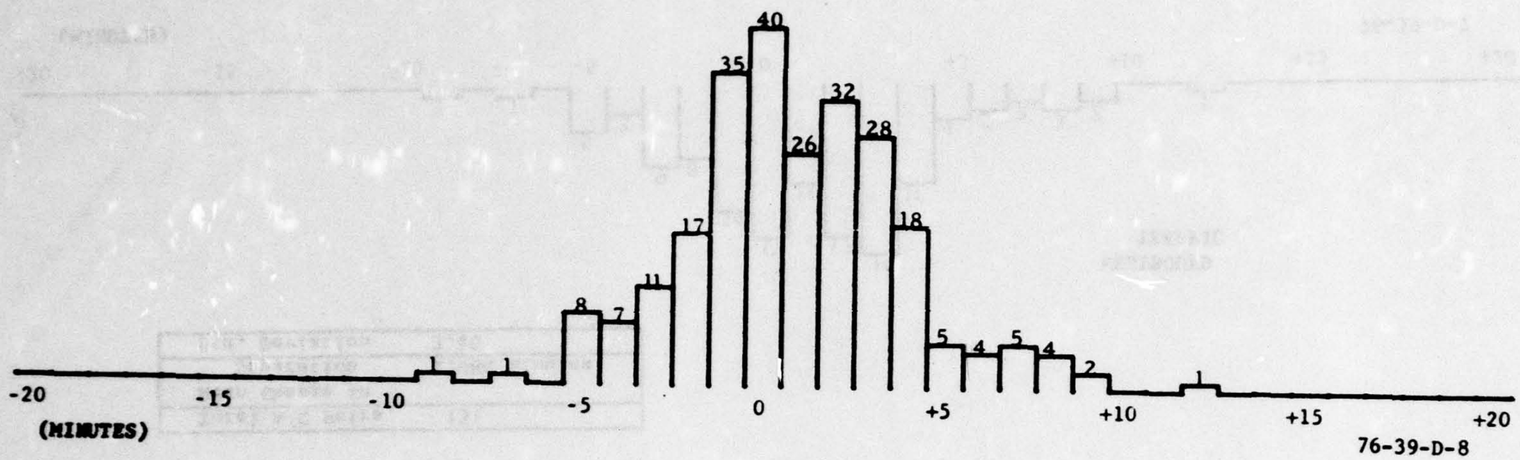


FIGURE C-8. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF .03 (X1 - 60 minutes) EAST AND WESTBOUND TRAFFIC

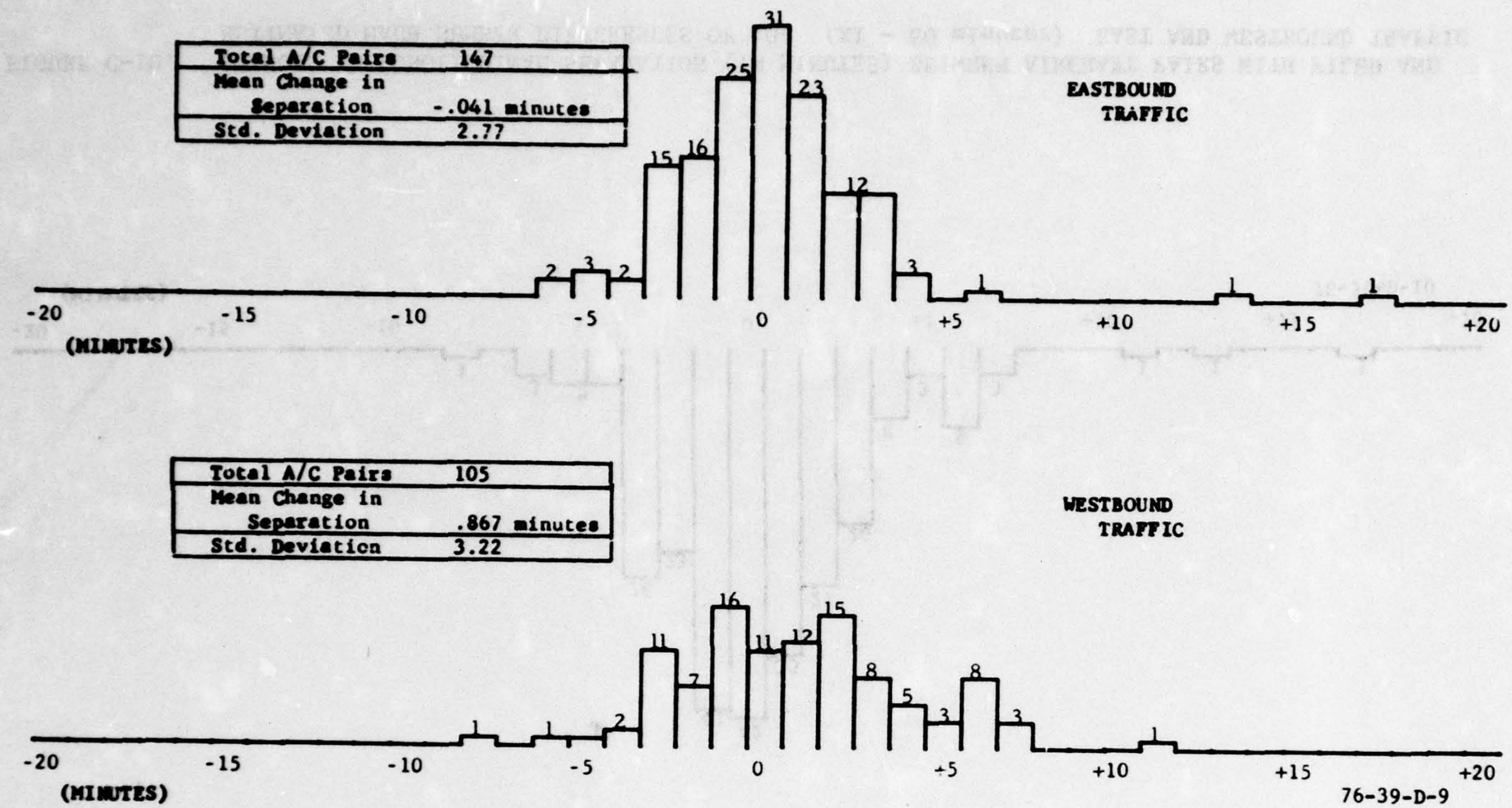


FIGURE C-9. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF .04 (X1 - 60 minutes)

Total A/C Pairs	252
Mean Change in Separation	.337 minutes
Std. Deviation	2.99

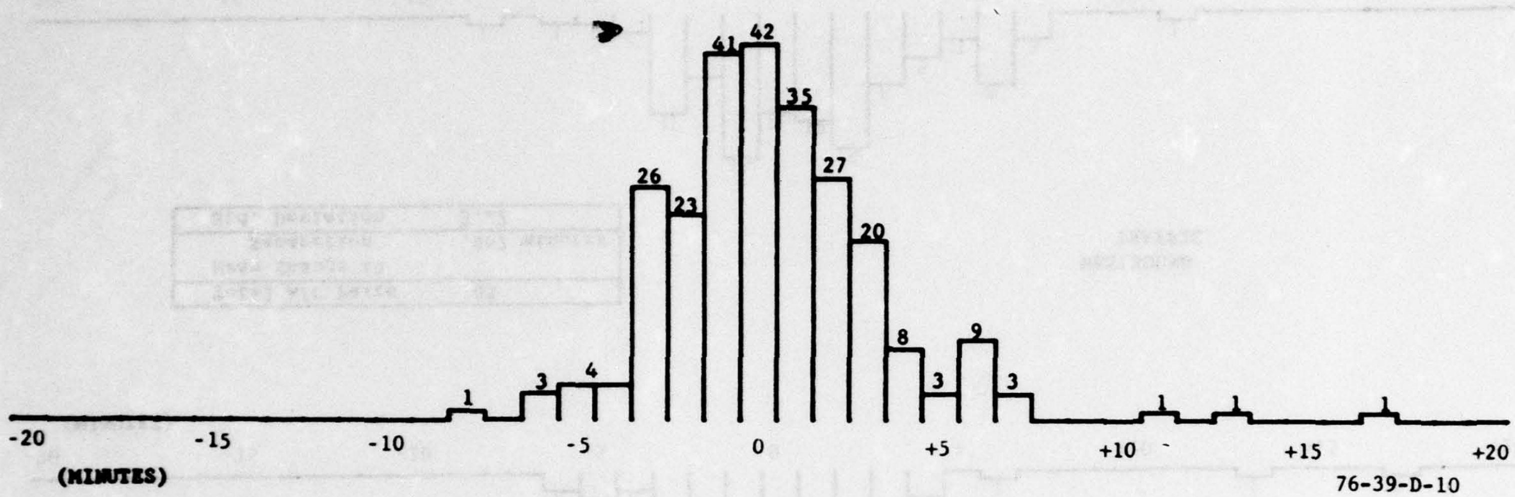


FIGURE C-10. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF .04 (X1 - 60 minutes) EAST AND WESTBOUND TRAFFIC

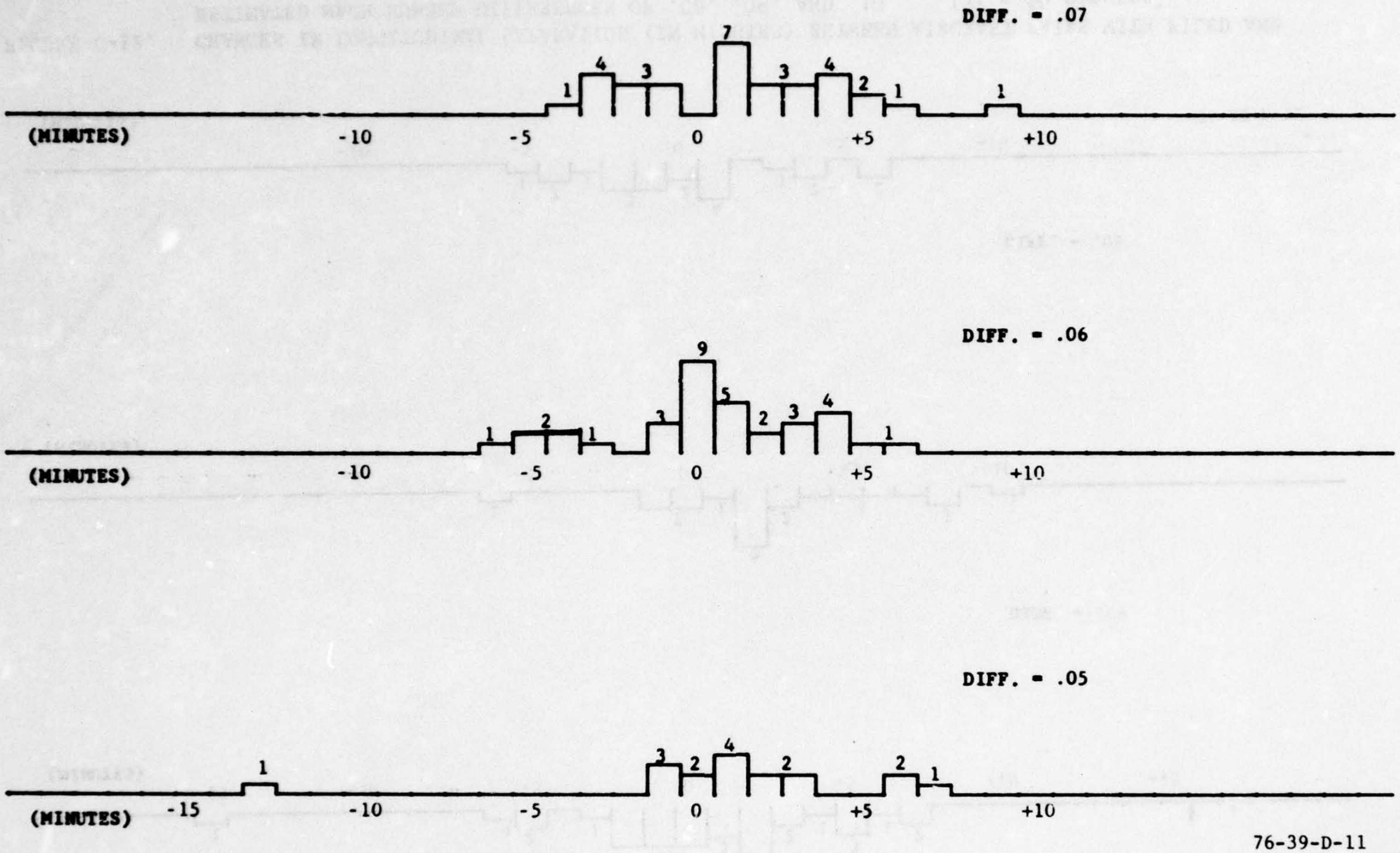


FIGURE C-11. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF .07, .06, AND .05 (X1 - 60 minutes) EAST AND WESTBOUND TRAFFIC

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LONGITUDINAL SEPARATION ANALYSIS OF THE CENTRAL EAST PACIFIC TR--ETC(U)
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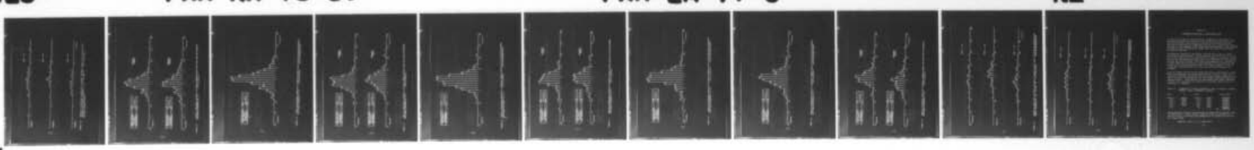

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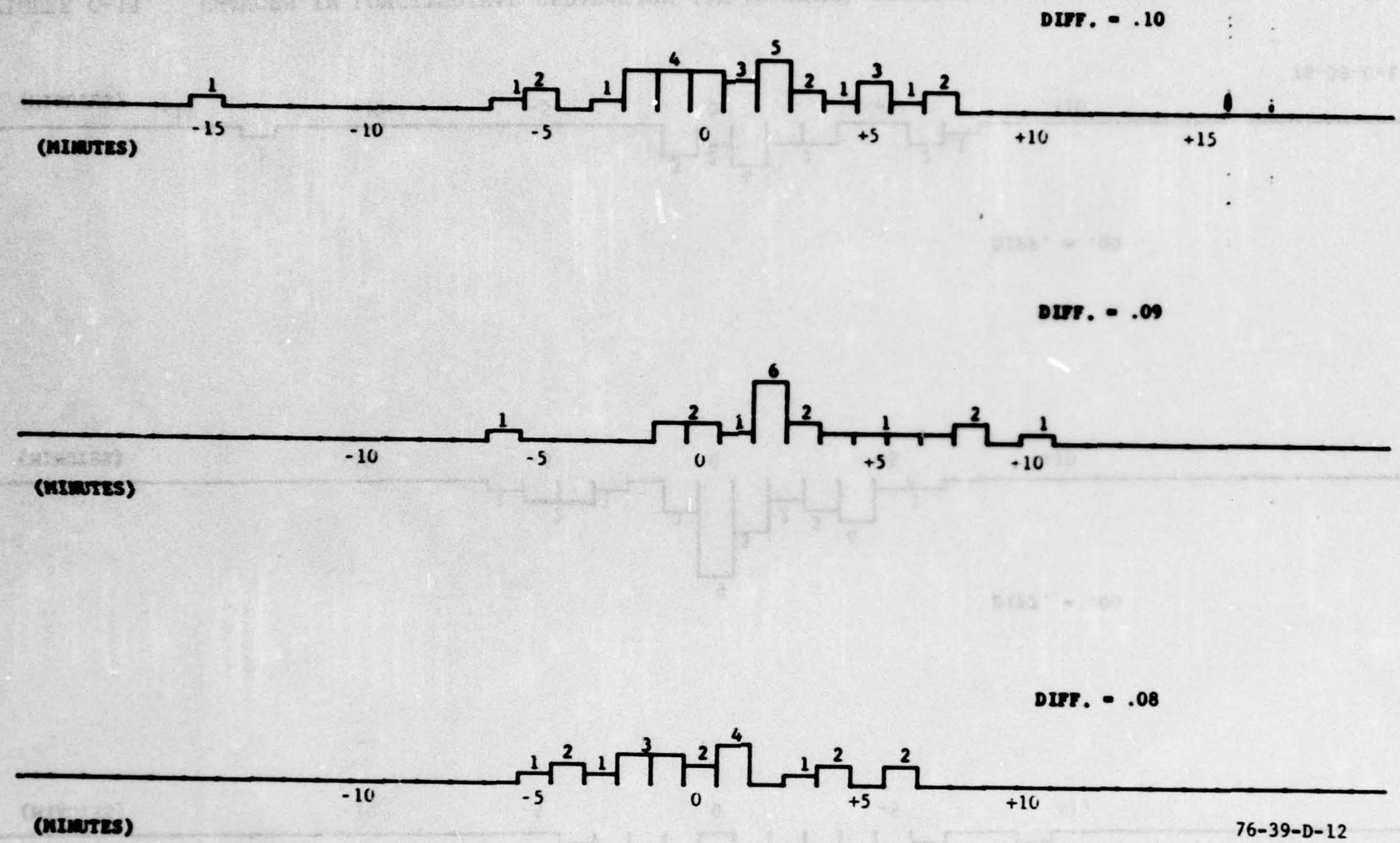
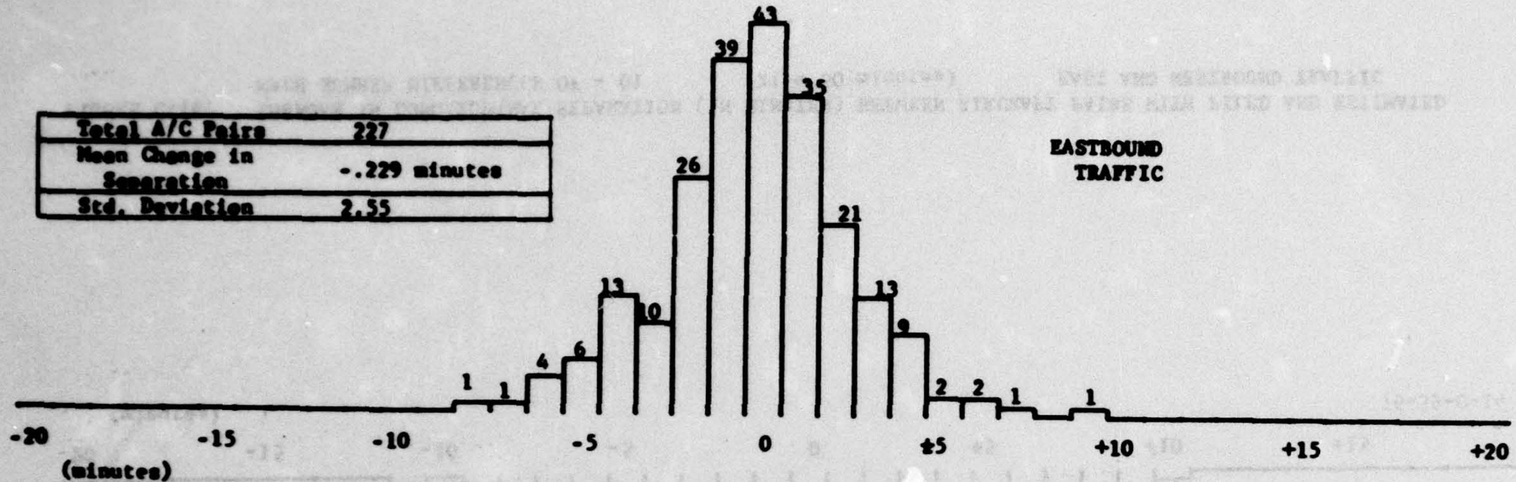
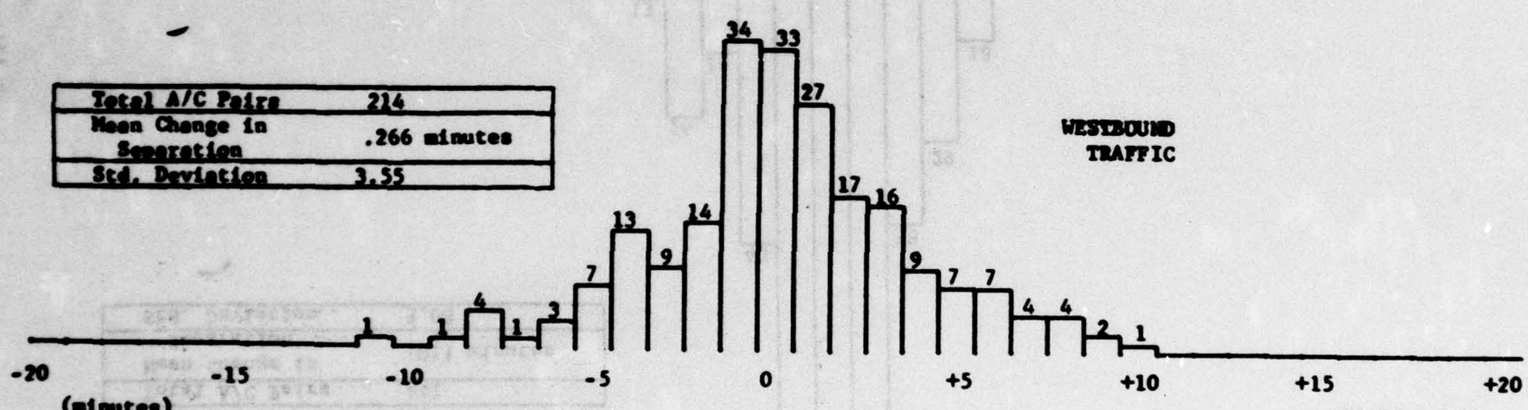


FIGURE C-12. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF .08, .09, AND .10 (X1 - 60 minutes) EAST AND WESTBOUND TRAFFIC

Total A/C Pairs	227
Mean Change in Separation	-.229 minutes
Std. Deviation	2.55



Total A/C Pairs	214
Mean Change in Separation	.266 minutes
Std. Deviation	3.55



76-39-C-13

FIGURE C-13. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF -.01 (X1 ≤ 60 minutes)

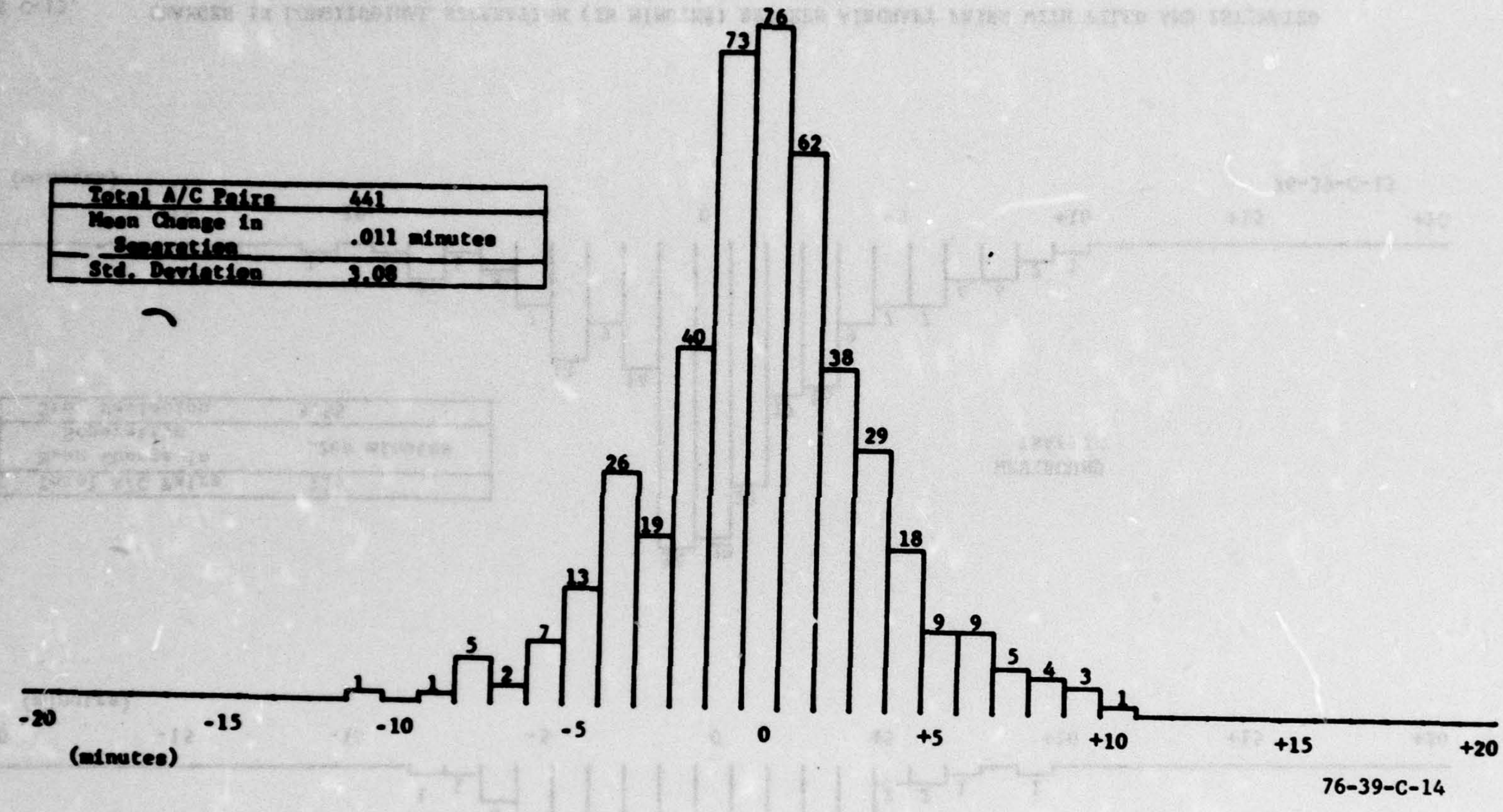
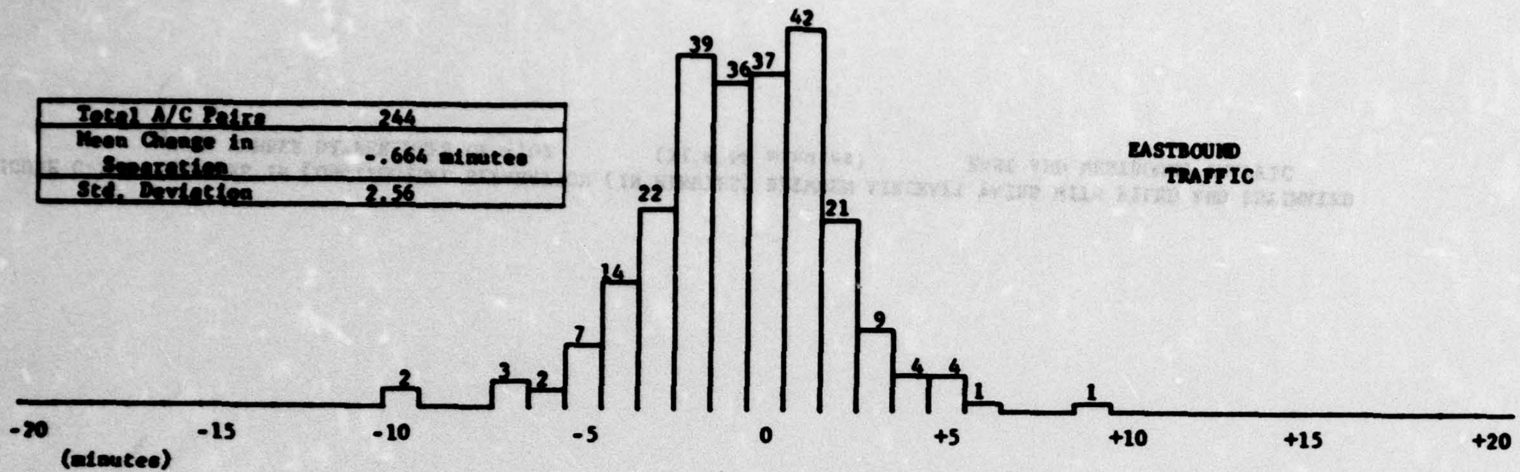


FIGURE C-14. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF -.01 (X1 ≙ 60 minutes) EAST AND WESTBOUND TRAFFIC



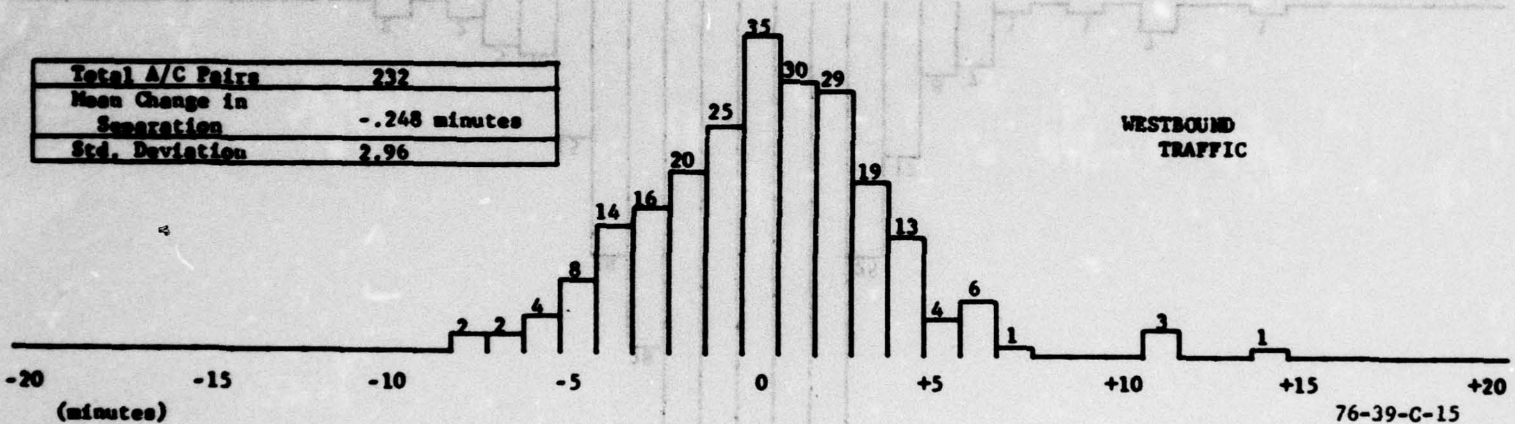


FIGURE C-15. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF -.02 (X1 ≤ 60 minutes)

Total A/C Pairs	476
Mean Change in Separation	-.248 minutes
Std. Deviation	2.96

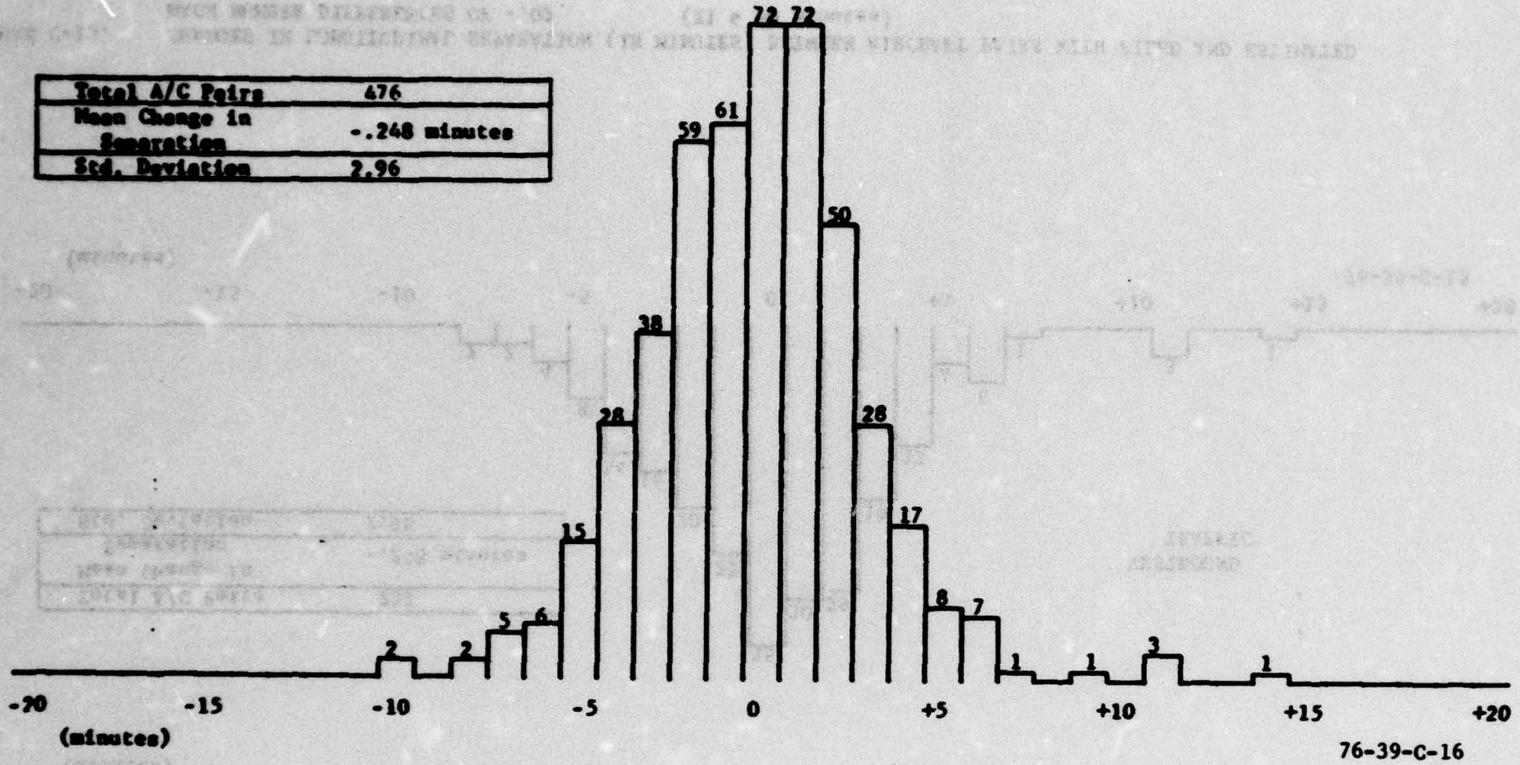
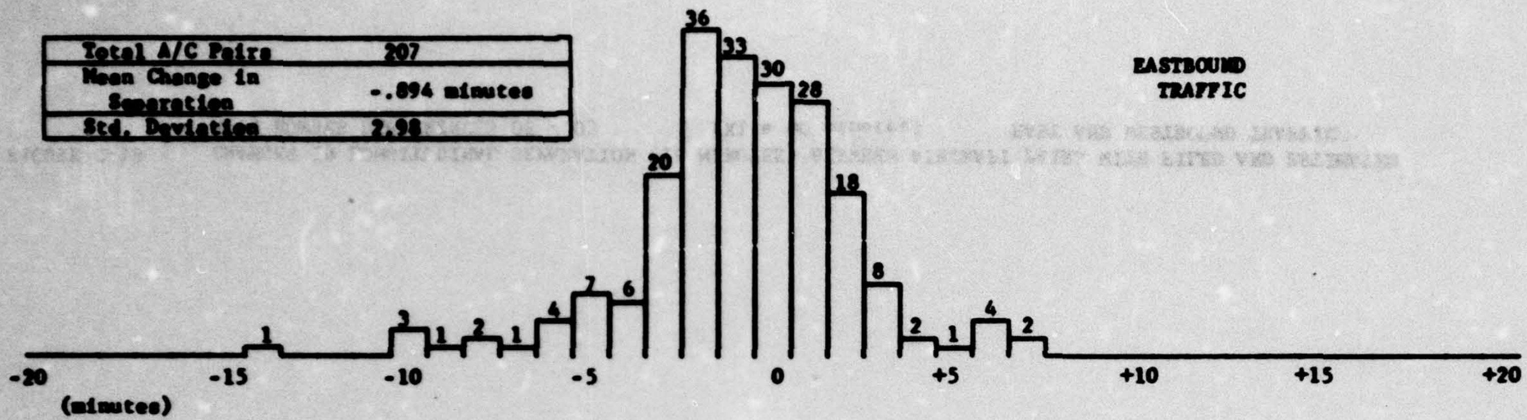
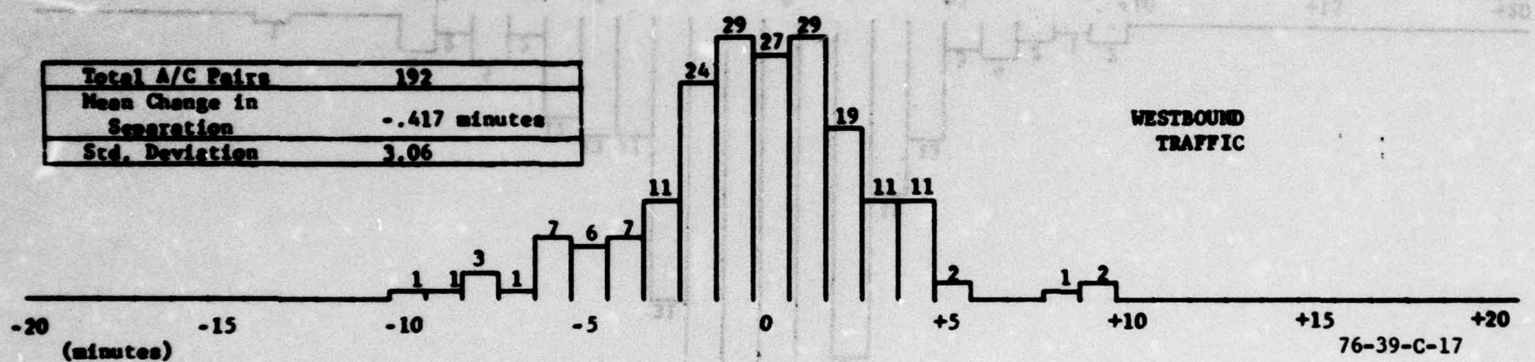


FIGURE C-16. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF -.02 (X1 ≤ 60 minutes) EAST AND WESTBOUND TRAFFIC

Total A/C Pairs	207
Mean Change in Separation	-.894 minutes
Std. Deviation	2.98



Total A/C Pairs	192
Mean Change in Separation	-.417 minutes
Std. Deviation	3.06



76-39-C-17

FIGURE C-17 CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF -.03 (X1 ≤ 60 minutes)

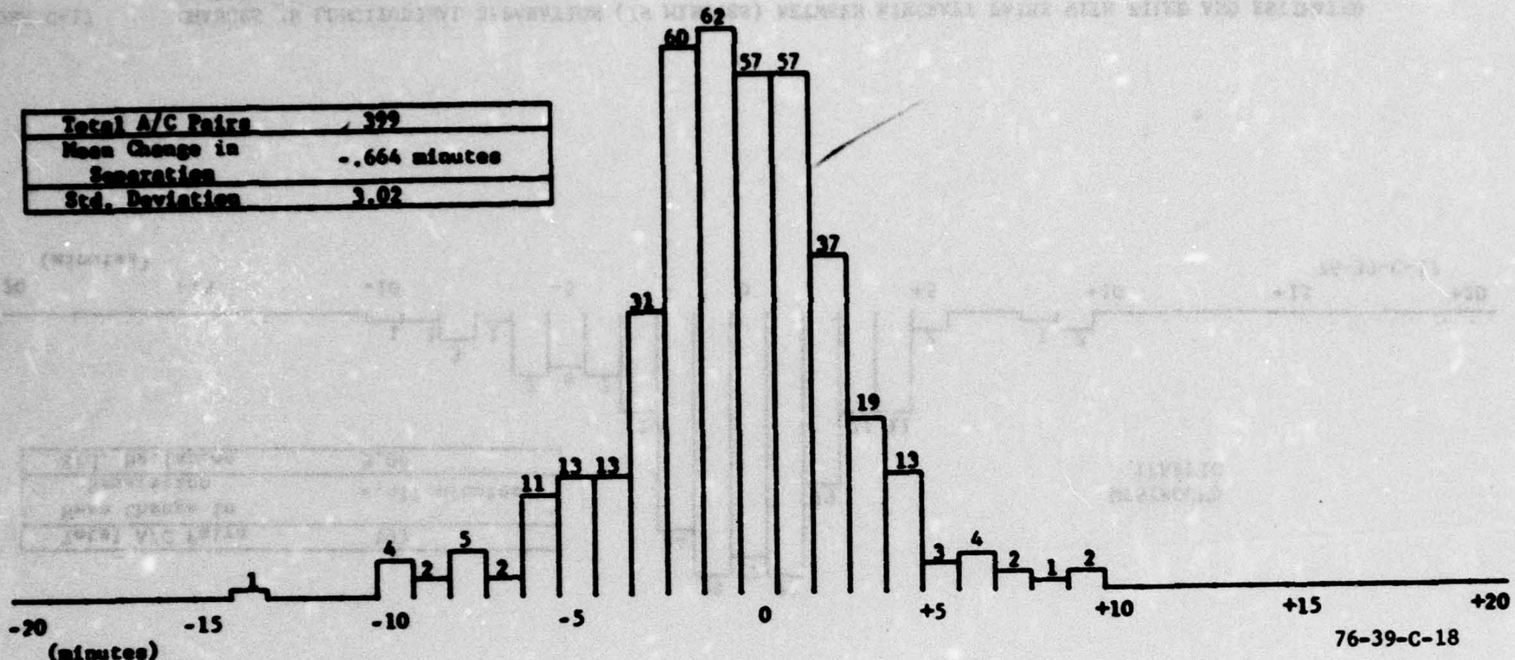


FIGURE C-18. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF -.03 (X1 ≤ 60 minutes) EAST AND WESTBOUND TRAFFIC

Total A/C Pairs	307
Mean Change in Separation	-.042 minutes
Std. Deviation	3.35

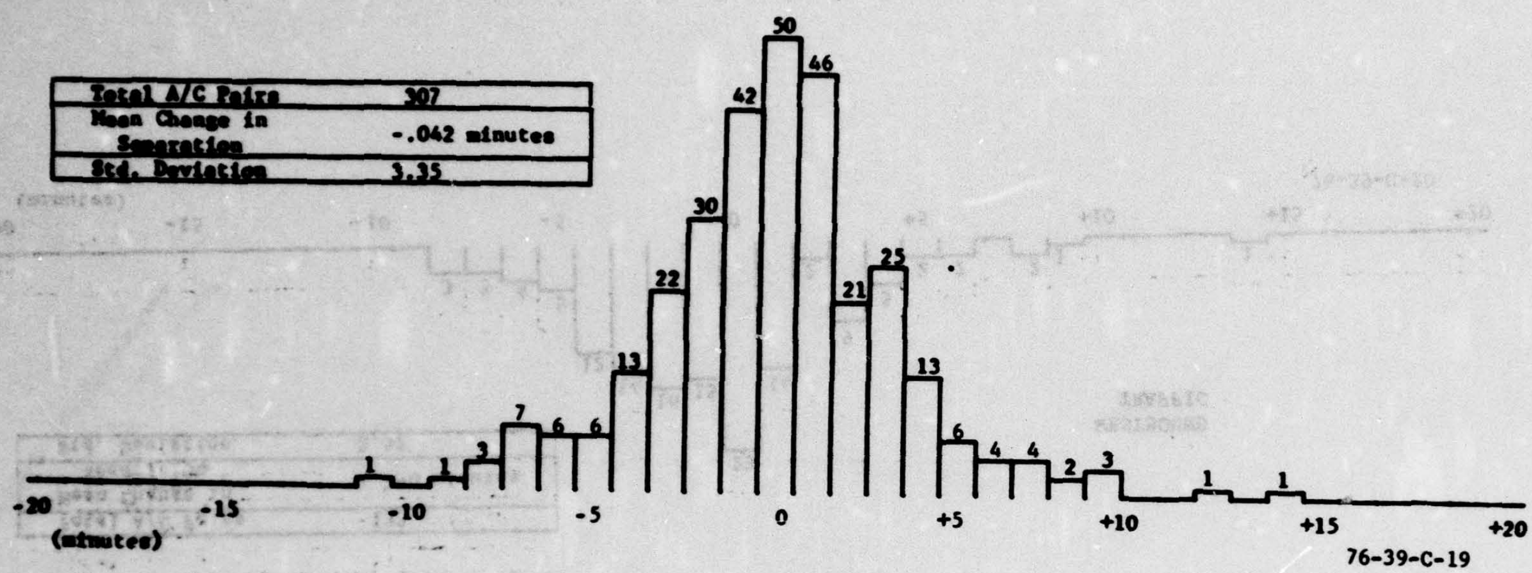


FIGURE C-19. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF -.04 (X1 ≤ 60 minutes) EAST AND WESTBOUND TRAFFIC

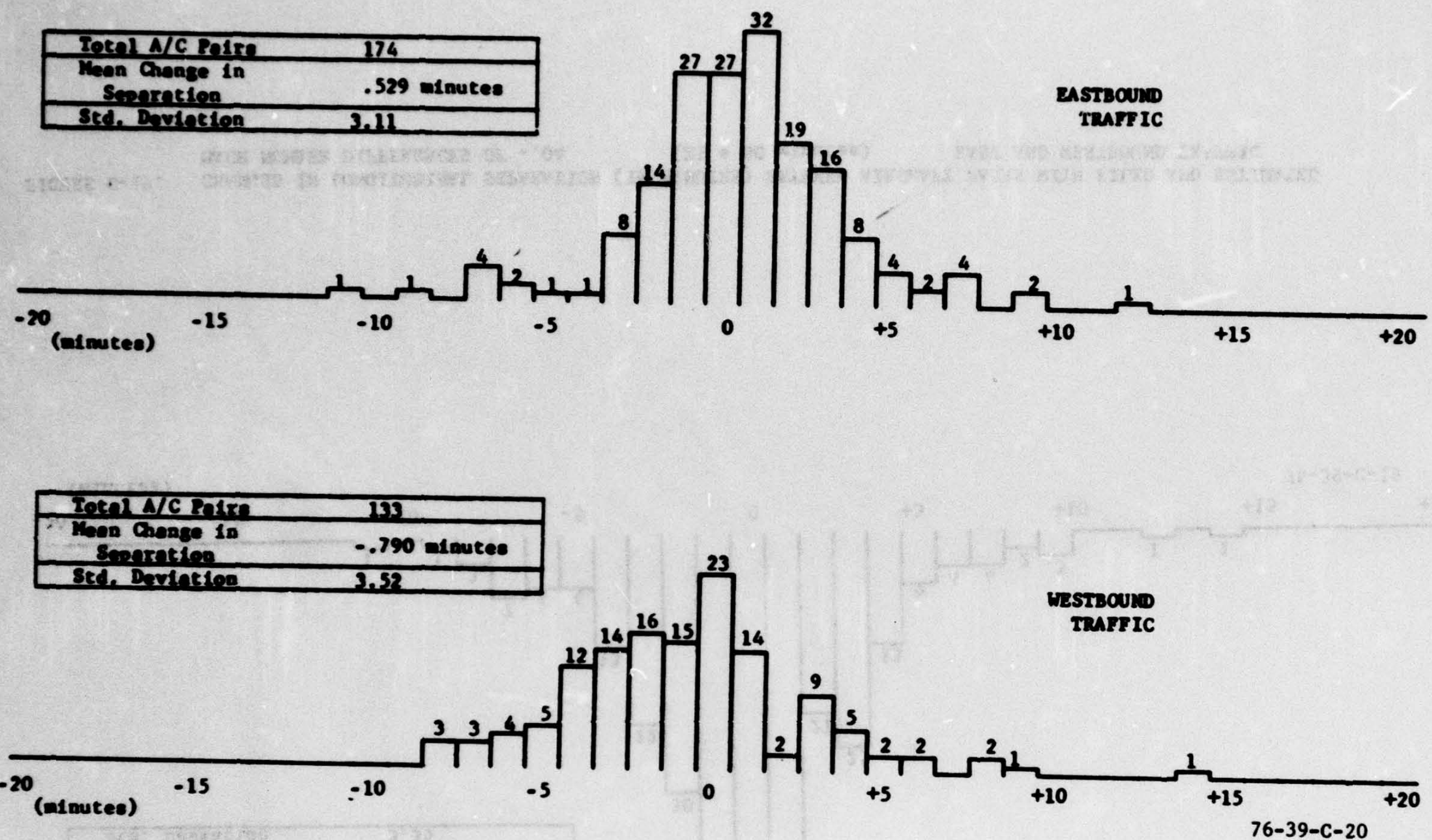
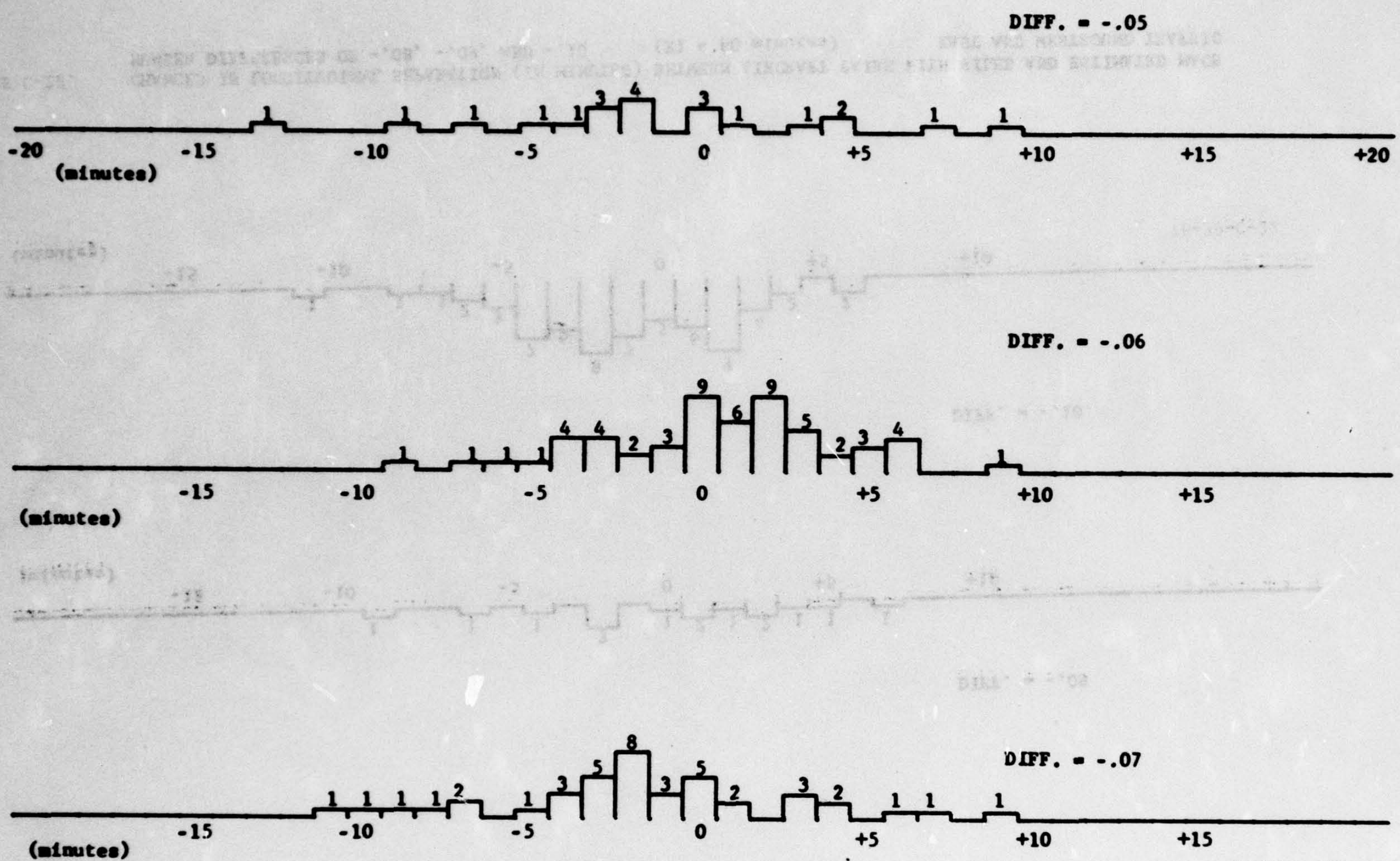


FIGURE C-20. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF -.04 (X1 ≤ 60 minutes)



76-39-C-21

FIGURE C-21. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF -.05, -.06, AND -.07 (X1 ≤ 60 minutes) EAST AND WESTBOUND PAIRS

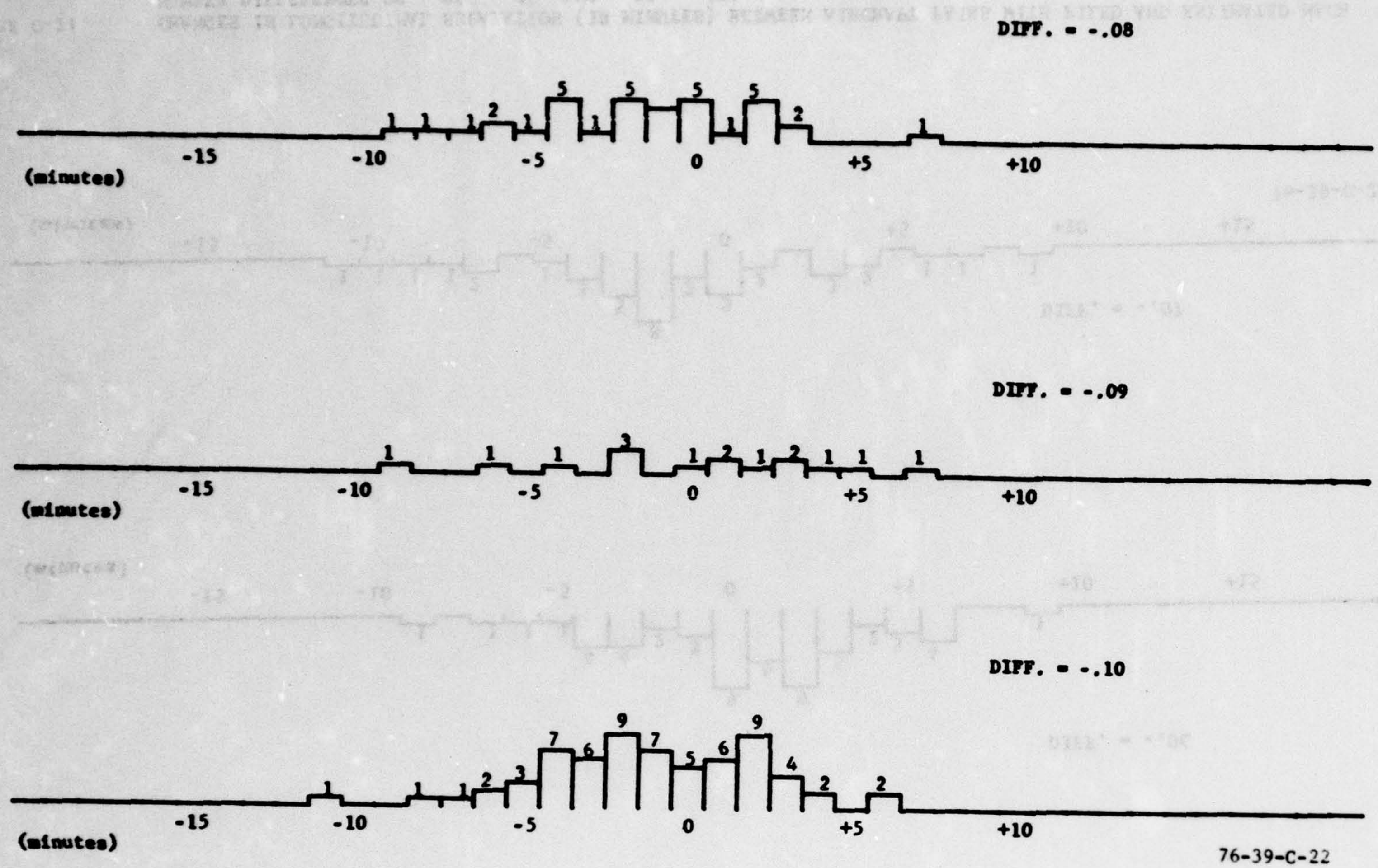


FIGURE C-22. CHANGES IN LONGITUDINAL SEPARATION (IN MINUTES) BETWEEN AIRCRAFT PAIRS WITH FILED AND ESTIMATED MACH NUMBER DIFFERENCES OF -.08, -.09, AND -.10 (X1 ≤ 60 minutes) EAST AND WESTBOUND TRAFFIC

APPENDIX D

INDEPENDENT DERIVATION OF LONGITUDINAL RISK

As part of the analytical work performed on longitudinal spacing and risk, the longitudinal risk was calculated. The procedure used followed the procedures of NAT/SPG as described in the minutes of the NAT/SPG V meeting. Using this approach and the refined data from the CEP, a longitudinal risk on the order of .537 accidents in 10^7 flying hours was calculated. Since this was an alarming result well beyond the target level of safety, a more detailed analysis was initiated.

An independent approach to longitudinal risk was taken to see if a nearly equal value could be obtained. In this approach, the general idea is to calculate the probability of a trailing aircraft reaching or passing the leading aircraft and then multiplying this value by the probability of simulataneous vertical and lateral overlap. This yields the probability of a collision on a single flight and is converted to the standard units of accidents per 10^7 flying hours by multiplying by the number of flights required to yield 10^7 flying hours and multiplying by 2, since each collision represents two accidents.

Using the refined CEP data and the folded distribution for gaining or losing time, the probability of gaining a given time is calculated. These values, along with the probability of starting with various initial separations, are used to calculate the probability of a given flight reaching or passing the leading aircraft. Using empirical data and applying the maximum likelihood principle, the distribution is truncated at the largest observed gain in separation of 17 minutes.

TABLE D-1. PROBABILITY OF INITIAL SEPARATION x PROB. OF GAINING t OR MORE MINUTES = PROB. OF REACHING OR PASSING

$E_X(t)$	x	$P_X(t)$		= $E_X(t)\ P_X(t)$
$E_X(12)$ =	.00012	$P_X(12)$ =	.00149	.00000018
(13) =	.00006	(13) =	.00117	.00000007
(14) =	.00036	(14) =	.00074	.00000027
(15) =	.00164	(15) =	.00021	.00000035
(16) =	.00316	(16) =	.00011	.00000034
(17) =		(17)	.00011	.00000046
			Sum	.0000162

Taking the table D-1 value calculated for the probability of passing, times the probability of lateral overlap (.0033) and times the probability of vertical overlap (.25) yields the probability of a collision from the rear on a single flight.

$$.00000162 \times .0033 \times .25 = 1.32825(10)^{-9}$$

The total probability of longitudinal collision is composed of three components: colliding from the rear, sideswiping during passing, and climbing or descending into the lead aircraft during passing. The problem for lateral or vertical sideswiping is to determine how far the aircraft could drift during the time it takes to pass. This, in essence, has the same effect as increasing the nominal cross-sectional area of the lead aircraft for a collision from the rear.

For an aircraft to gain 15 minutes in the distance between 130° and 150° longitude in the track system, the following rationale was applied. A distance of 1,163 nmi was calculated to be the average CEP route distance between these longitudes. The average aircraft speed was calculated to be 480 knots, and applying the average winds, it was found that to gain this amount of time over this distance required a relative velocity differential of at least 49.33 knots. Average flight time over the distance is found to be 145 minutes.

To find the effective increase in nominal cross section, we first need the time of passing, which is $2\lambda_x \div |\bar{\dot{x}}|$ (.066 miles ÷ 49.33 knots = .0013 hours). Multiplying this time by the lateral and vertical average velocities yields the increases in the effective nominal dimensions of the aircraft.

$$= .0013 \text{ hours} \times 20 \text{ knots} = .0268 \text{ miles}$$

$$= .0013 \text{ hours} \times 1 \text{ knot} = .0013 \text{ miles}$$

The cross section $(2\lambda_y \times 2\lambda_z)$ is .066 x .017 = .001122 square miles and the nominal effective cross section accounting for sideswipes is (.066 + .0268) x (.017 + .0013) = .001701 square miles. The ratio of these two areas

$\left(\frac{.001701}{.001122} = 1.52\right)$ multiplied by the probability of collision from the rear yields the total longitudinal collision risk for a single flight $(1.52 \times 1.32825(10)^{-9} = 2.014(10)^{-9})$.

The number of flights necessary for 10^7 flying hours is 10^7 hours ÷ $\frac{145 \text{ minutes}}{60 \text{ minutes/hr}} = 4.137(10)^6$

Multiplying the number of flights and probability of collision per flight times 2 for the fact that each incident represents 2 accidents yields the final collision risk.

$$4.137(10)^6 \times 2.014(10)^{-9} \times 2 = .0166 \text{ accidents in } 10^7 \text{ hours.}$$

This value, being so vastly different from the NAT/SPG V approach, led to a more in-depth study of longitudinal collision risk. Review of the literature describing the NAT/SPG risk model revealed that P_x in the NAT/SPG model is the proportion of time aircraft spend adjacent or passing one another. NAT/SPG V used P_x to be occurrences rather than proportion of time.

Performing longitudinal risk using the NAT/SPG model and using 49.33 knots relative longitudinal velocity rather than the NAT/SPG 26 knots (aircraft could never close 15 minutes at 26 knots relative velocity) but disregarding the NAT/SPG approach yields the following:

$$N_{ax} = 2x10^7 \left[\frac{\overline{|\dot{x}|}}{2\lambda_x} + \frac{\overline{|\dot{y}(0)|}}{2\lambda_y} + \frac{\overline{|\dot{z}(0)|}}{2\lambda_z} \right] P_y\ (0)\ P_z\ (0)\ \pi_x$$

where $\pi_x = \Sigma E_x(t)\ P_x(t)$

The $P_x(t)$ shown earlier must be converted from probability of occurrence to proportion of time.

This is accomplished by taking the distance flown in passing $2\lambda_x$ (.066 nmi) and dividing by relative longitudinal velocity (49.33 knots) to get passing time and finally dividing by total flight time $\left(\frac{145}{60} \text{ hours}\right)$.

$$\text{Factor} = \frac{.066}{49.33} \frac{(60)}{145} = 5.536\ (10)^{-4}$$

The sum of the $E_x(t)\ P_x(t)$ from table D-1 multiplied by this factor gives the π_x value.

Substituting numerical values in the NAT/SPG model

$$N_{ax} = 2(10)^7 \left[\frac{49.33}{2(.033)} + \frac{20}{2(.033)} + \frac{1}{2(.0085)} \right] (.0033)(.25)(5.536)(10)^{-4}\ 1.62(10)^{-6}$$

N_{ax} = .0168 collisions in 10^7 flying hours

This result is very nearly equal to the result obtained using the independent approach.